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Eighth Semiannual Technical Report

March 1977

For the Project

INTEGRATED DOD VOICE & DATA NETWORKS
AND GROUND PACKET RADIO TECHNOLOGY

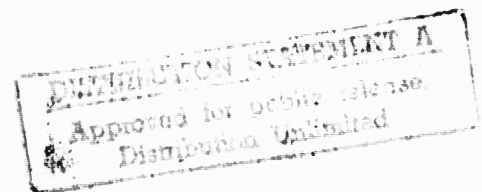
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TOPOLOGICAL GATEWAY PLACEMENT

STRATEGIES

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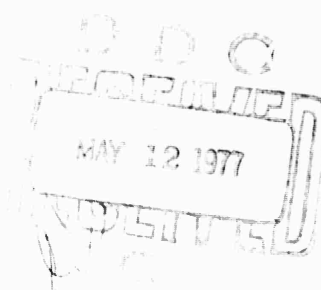
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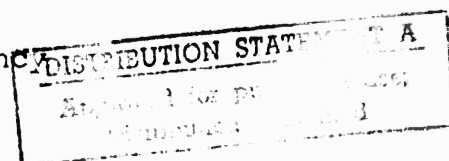


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EIGHTH SEMIANNUAL TECHNICAL REPORTTABLE OF CONTENTSVOLUME 1INTEGRATED DOD VOICE AND DATA NETWORKS

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FOR TELECOMMUNICATIONS
- CHAPTER 2 ANALYSIS OF INTEGRATED SWITCHING LINKS
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CHAPTER 7

TOPOLOGICAL DESIGN OF GATEWAYS FOR PACKET
SWITCHED INTER-NETWORK COMMUNICATIONS

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CHAPTER 7TOPOLOGICAL DESIGN OF GATEWAYS FOR PACKET
SWITCHED INTER-NETWORK COMMUNICATIONS7.1. INTRODUCTION AND SUMMARY

In this Chapter we consider the topological design issues associated with packet-switched network intercommunication. In particular, we present an effective (heuristic) solution procedure for a simplified internet topological model, and illustrate the design tradeoffs by applying the procedure to the interconnection of a multi-network example, and the interconnection of ARPANET and a simplified model of AUTODIN II packet-switched backbone network.

Internetwork communication has become an increasingly active area of research in the last few years. However, up to now, most research efforts have been concentrated on the protocol and gateway design issues, [CERF, 1974], [CERF, 1975], [BBN, 1975]. The purpose of this study is to investigate the topological design related issues.

In Section 7.2, a brief survey on the current work in network intercommunication is given. A general approach to establish internet communication is to connect the networks through "gateways", or "gateway-halves" (GH). The gateway-halves together with the (actual or pseudo) links connecting them form a so-called "gateway-half virtual network". A fundamental criterion in internet communication is that the internal operations of the individual networks should not be interfered with. Based on this so-called independence principle, some general requirements can be deduced. For example, to allow the local net better protection against the internet traffic, the gateway-halves should connect to the networks at the Host level; also, an internet packet should appear as a local packet in the local nets. Several internet end-to-end protocol issues are addressed. The first issue is whether internet packet fragmentation should be done at the gateway-halves. Other issues related to internet flow control and error control are: Should flow control be

performed on letters or on fragments? Should error control be made optional? Should retransmission between gateway-halves be used? Each of the issues is discussed briefly. We then list the basic gateway-half functional requirements: message processing between two networks, intergateway routing, access control, accounting, statistics gathering, internetwork message fragmentation, congestion control and intergateway retransmission.

In Section 7.3 we present a formulation of the general internetwork topological design problem, and indicate of the inherent difficulties. We then examine the alternatives in internet routing and network design. The important issues are: Should a fixed or an adaptive routing policy be used? Should the Hosts participate in route selection? Should a single level or a hierarchical routing policy be used? Can the local requirements be routed through the internet and use other networks' resources? Can the local net topology and link capacities be modified in the internet design process? For some of the issues, reasonable decisions can be made based on the local net independence principle and previous single network design experience, e.g., hierarchical adaptive routing policies are preferred over single level fixed routing policies. For other issues, the answers are not so clear, and for some the non-technical considerations may be the dominant factors in decision-making. An internet routing model is presented in Section 7.4. The routing of an internet packet is carried out in three stages.

1. Local net routing from the source switch (or Host) to the source regional gateway-half.
2. Gateway-half virtual net routing from the source regional gateway-half to the destination regional gateway-half.
3. Local net routing from the destination regional gateway-half to the destination switch (or Host).

With this routing model, the original Host-to-Host traffic requirements reduce to the following three types: Local net switch to switch requirements, local net switch to gateway-half requirements induced from the internet requirements, gateway-half virtual net to gateway-half requirements, induced from the internet requirements. The internet and local end-to-end delay constraints can then be reformulated in terms of these three types of requirements.

Based on the internet routing model, a simplified internetwork topological design problem is formulated in Section 7.5. A design procedure, using extensions of existing single net design techniques, is presented. Briefly, the procedure is as follows: First, based on the internet traffic requirements and the local net characteristics, a set of gateway-halves is selected from each net. The routes for the local (switch to switch and switch to gateway-half) requirements are then determined in each local net. If allowed, the local net topologies and link capacities are also optimized. An estimate on the incremental delay per unit incremental flow can then be determined between each pair of gateway-halves residing in the same local net. This information is used for the gateway-half virtual net routing and topological design. The procedure can be applied iteratively to obtain design improvements. A procedure for selecting the gateway-halves, based on methodologies similar to backbone switch selection procedure [NAC, 1976a] and satellite switch selection procedure [NAC, 1976b] is also presented.

The design procedures have been implemented on a PDP-10 based on modifications and extensions of existing NAC single network, single traffic class interactive design system. Due to the multi-network, multi-traffic classes nature of the internetwork design problem, the modifications are substantial. These programs have been applied to study the interconnection problem of a multi-network model and the interconnection of ARPANET and AUTODIN II. Below we briefly summarize the main findings. Detailed design results are reported in Section 7.6.

On the multi-network model, studies were carried out based on the following assumptions:

1. The sum of the local requirement and the internet requirement is constant;
2. The local traffic requirement is distributed uniformly among the local switch pairs;
3. The internet traffic requirement is distributed uniformly among the internet switch pairs.

The following observations emerge:

1. The higher the proportion of internet traffic requirement, the higher the total system cost. (Note that the total traffic is constant).
2. Suppose each local net is optimally designed for the local traffic, and is not allowed to change. Then in order to accommodate the internet traffic (even under the assumption that total amount of local and internet requirement is constant), gateway-halves are required at at least half of the switch locations.
3. Suppose only a moderate number of gateway-halves are used. By allowing modifications on the local net link capacities (but not topologies), good internet design can be obtained.

4. The total cost for an interconnected system is of the same order as the total cost for a fully integrated system, assuming that no extra protocol overhead, no software modification cost is required for the later system.

On the ARPANET-AUTODIN II model, studies were carried out assuming fixed local net topologies (link capacities may be modified), and fixed local net traffic requirements. The peculiarity of this system is that the ARPANET traffic level and utilization are very low but the number of switches is large. Studies were carried out to determine the maximum possible internet throughput levels for various number of gateway-halves, under the assumption that neither ARPANET nor AUTODIN II is allowed to change. Figure 1 shows the maximum internet throughput as a function of the number of gateway-halves used in the ARPANET. Moreover, it was observed that by allowing modification in local net link capacities, only minor cost savings (5%) can be achieved at the base unit costs (\$5/mile/mo. for 50 Kbps trunk lines, and \$2K/mo. for the gateway-half modules). By parametrizing the unit component costs, it was observed that the cost differences between designs with local nets fixed and designs with local nets changeable are quite sensitive to changes in unit communications cost, but less sensitive to changes in unit gateway-half module cost. When the cost of gateway-halves increases, the cost differences between the two types of designs becomes more apparent. Figure 2 shows the cost differences between the fixed local net designs and changeable local net designs, for different internet throughput levels and different unit component costs. The cost difference between the two options (fixed or modifiable local nets) ranges from 1% to 12%. For low gateway-half cost, the cost difference is more sensitive to communication cost than to internet throughput level. When the gateway-half cost is increased, then the cost difference becomes sensitive to the internet throughput level.

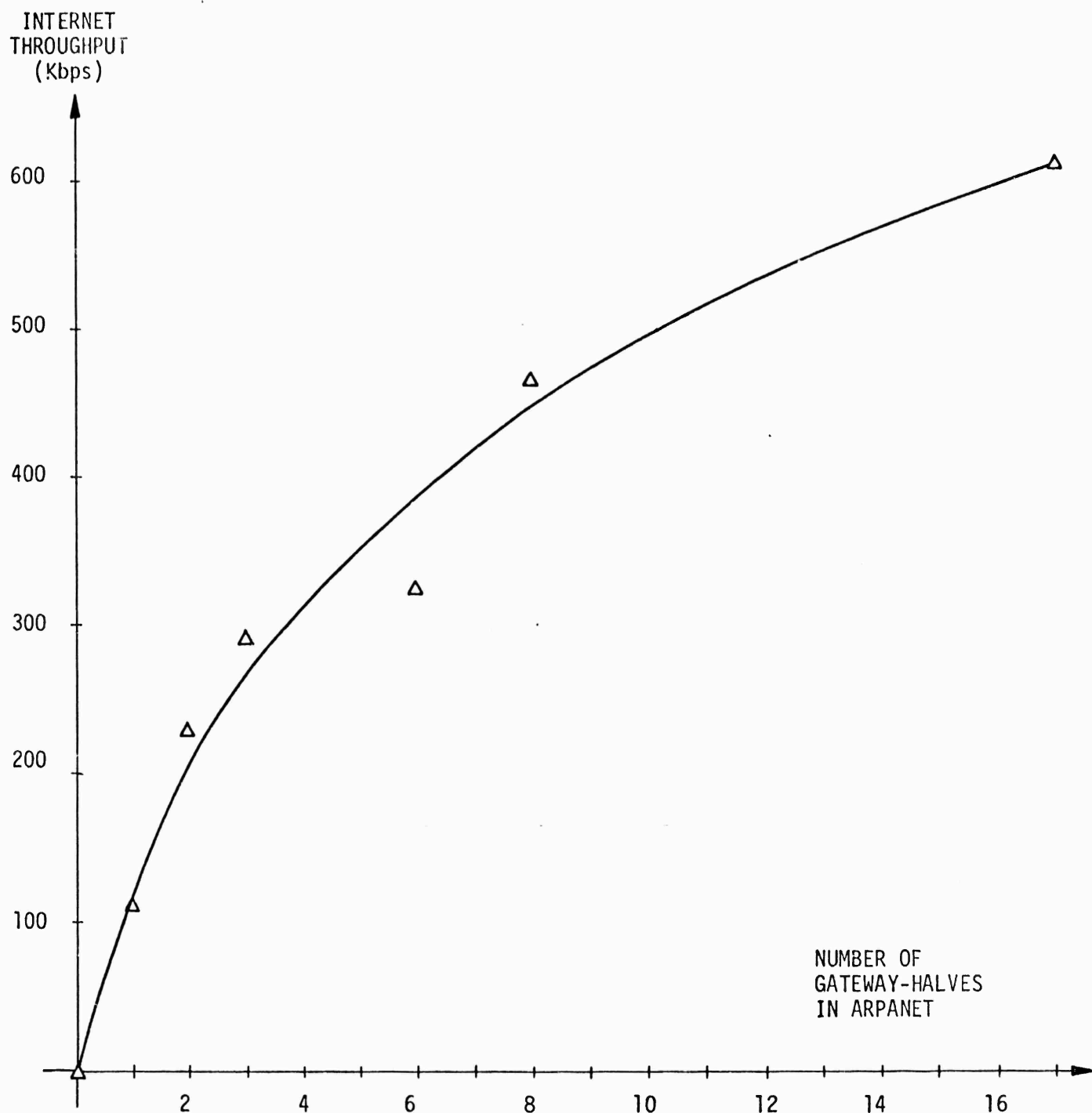


FIGURE 1: INTERNET THROUGHPUT VS. NUMBER OF GATEWAY-HALVES USED IN ARPANET:
ARPANET - AUTODIN II DATA BASE; FIXED LOCAL NETS

TOTAL SYSTEM COST
(K\$/MO.)

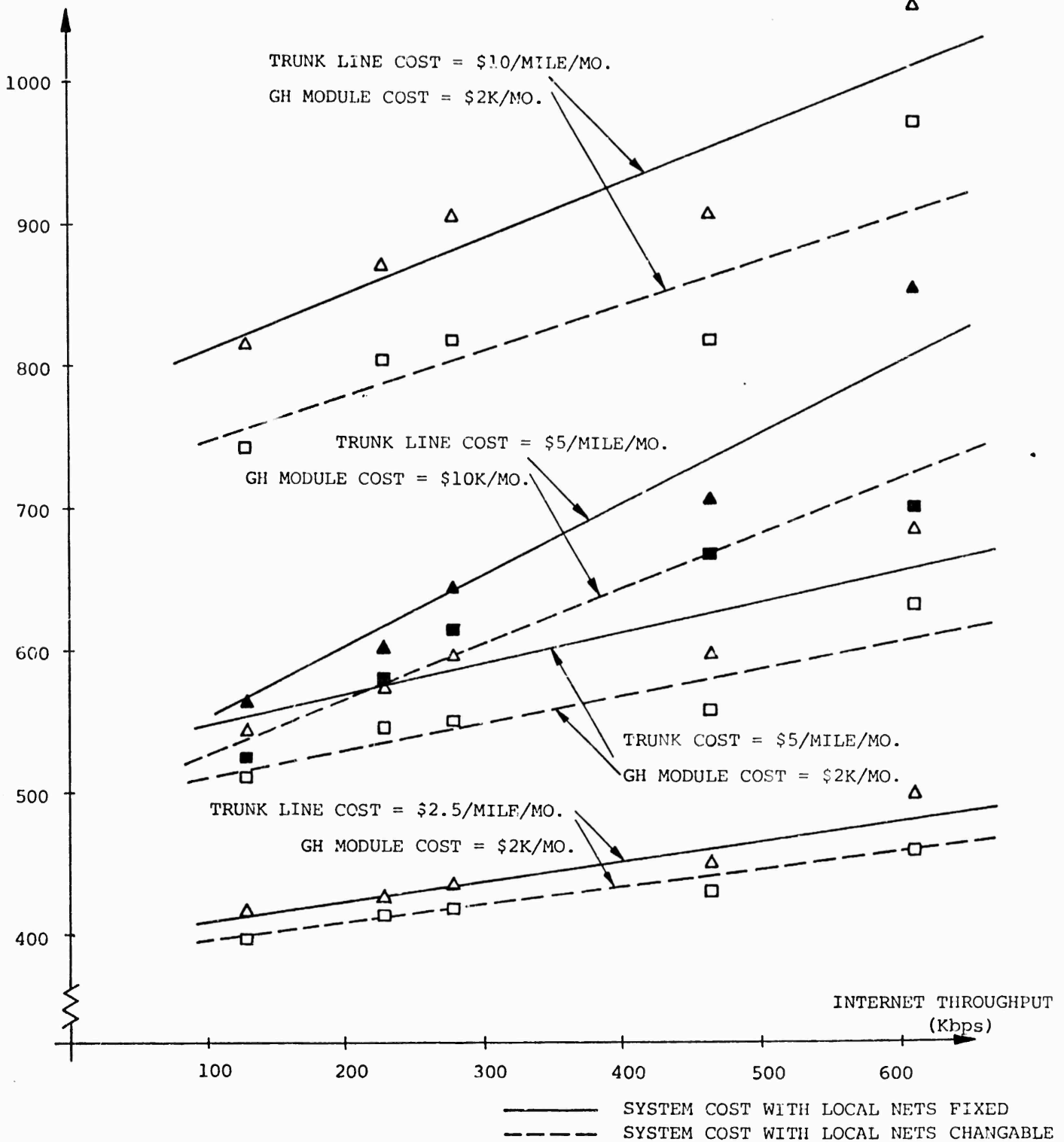


FIGURE 2: TOTAL SYSTEM COST COMPARISON BETWEEN DESIGNS
WITH LOCAL NET FIXED AND DESIGNS WITH LOCAL
NETS MODIFIABLE: ARPANET - AUTODIN II DATA BASE

7.2. BASIC FRAMEWORK FOR NETWORK INTERCONNECTION

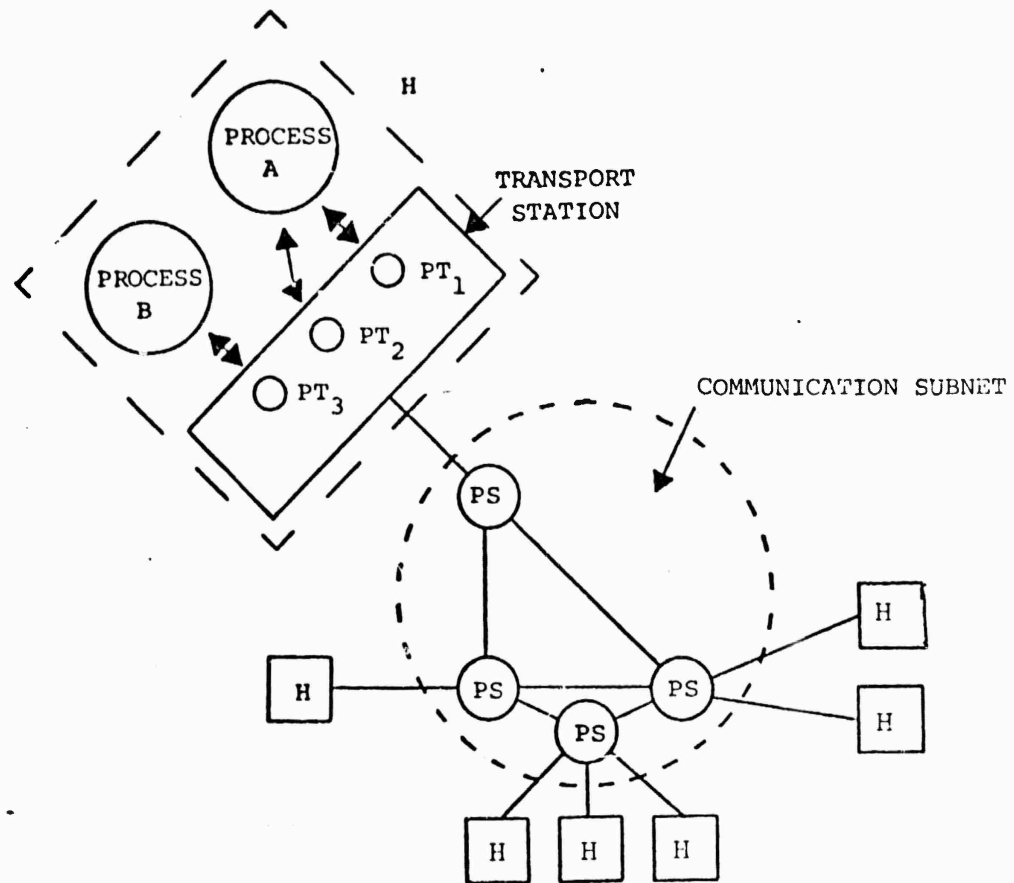
In this section we present the basic framework and the relevant protocol and gateway issues for internetwork communication. General surveys on network interconnection can be found in [CERF, 1974] [SUNSHINE, 1977] [ROBERTS, 1976] [BBN, 1975].

7.2.1 Basic Entities in Internetworking

First, we briefly examine the elements of a packet-switched network (Figure 3). A packet-switched network is composed of a set of computer resources (Hosts), a set of one or more packet switches (network nodes), and a set of communication channels (network links) that interconnect the packet switches. A Host may have several active processes which communicate with processes in the Host and processes on other Hosts. It is assumed that each Host will contain a transport station responsible for multiplexing the interface with the communication subnet, and "adding value" to the packet switching service. For identification purposes, we suppose that each process communicates through one or several ports in the transport station. Each port is assigned a unique name (or address) in the multi-network context (i.e., even though the addresses for the ports may change dynamically, at any moment no two ports can have the same address). Thus a transport station can be considered as a collection of ports. The communication between a source port and a destination port is effected by an association between the two ports.

The communication subnet of a packet-switched network usually exhibits the following common operational characteristics: [McKENZIE, 1974]

- Although the average delay between accepting and delivering a packet is relatively small, the variance may be large.



H - HOST
 PS - PACKET SWITCH
 PT - PORT

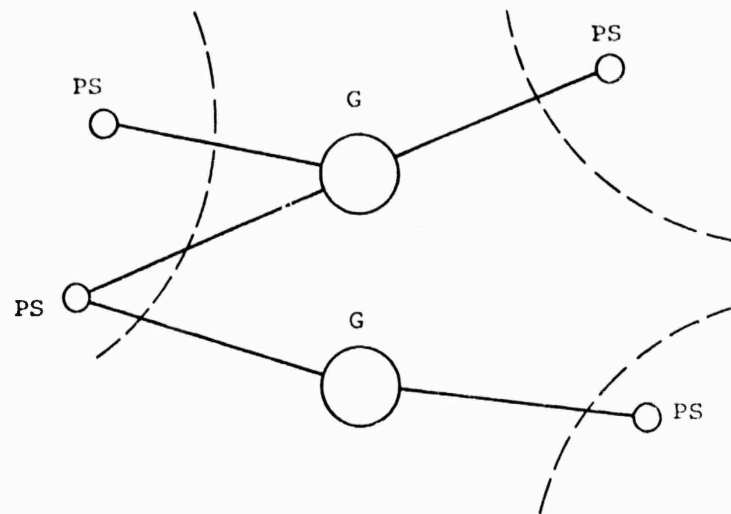
FIGURE 3: A PACKET-SWITCHED NETWORK

- Packets may be delivered in an order different from that in which they were accepted.
- Duplicate copies of packets may be delivered.
- Some packets may not be delivered, (with a non-negligible probability).
- Bit error probability in delivered packets is small.

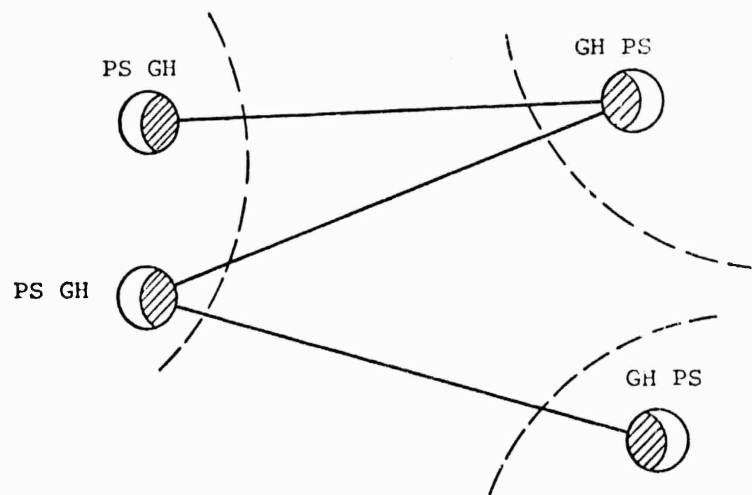
However, individual packet-switched networks may be different in implementation as follows:

- Each network may have distinct ways of addressing the receiver.
- Each network has its own routing, fault detection, flow control techniques.
- Each network has its own format of packets and its own Host/node and Host/Host protocols. The maximum packet size may be different in different networks.
- Each network has its own time delay characteristics in accepting, delivering and transporting the data.

The interconnection of a pair of (or several) packet-switched networks can be done in one of two ways (see Figure 4):



(A) GATEWAY CONNECTION MODEL



(B) GATEWAY-HALF CONNECTION MODEL

PS - PACKET SWITCH

G - GATEWAY

GH - GATEWAY-HALF

FIGURE 4: INTERNET CONNECTION ALTERNATIVES

1. Via gateway units which act as hosts to two (or several) networks,
2. Via connection through one or several pairs of gateway-halves (GH's) each residing as a host in one network.

The merits and weaknesses of the Gateway and Gateway Halves approaches as well as the functions to be included in these devices have been explored in [BBN, 1975], [CERF, 1974], [DAY, 1975], [INWG, 1975], [McKENZIE, 1974], [POUTIN, 1974] and others, and is not elaborated upon. In this chapter, the discussion will be carried out under the GH model, although most of the results are equally valid under the gateway model.

The gateway-halves, together with the interconnecting links, form a "gateway-half virtual network" (see Figure 5). The GH's residing in different networks are connected by intergateway links in order to effect internetwork communication. Some of the GH's residing in the same network may also be connected by intergateway links in order to effect fast transmission. Moreover, the GH's residing in the same network are connected by "pseudo-links" which correspond to local net paths between the GH's. Thus, the GH's residing in the same network together with the interconnecting pseudo-links form a complete graph.

7.2.2 Basic Operational Requirements for Internetworking

Because packet-switching technology is still in its early development stage, it may be premature to force a common standard on all the networks. Hence, the fundamental principal in internetwork communication is that it should not interfere with the internal operation of the individual networks (even though some networks may choose to modify their operations to making internetworking easier). Thus the individual network differences mentioned earlier should be taken into account.

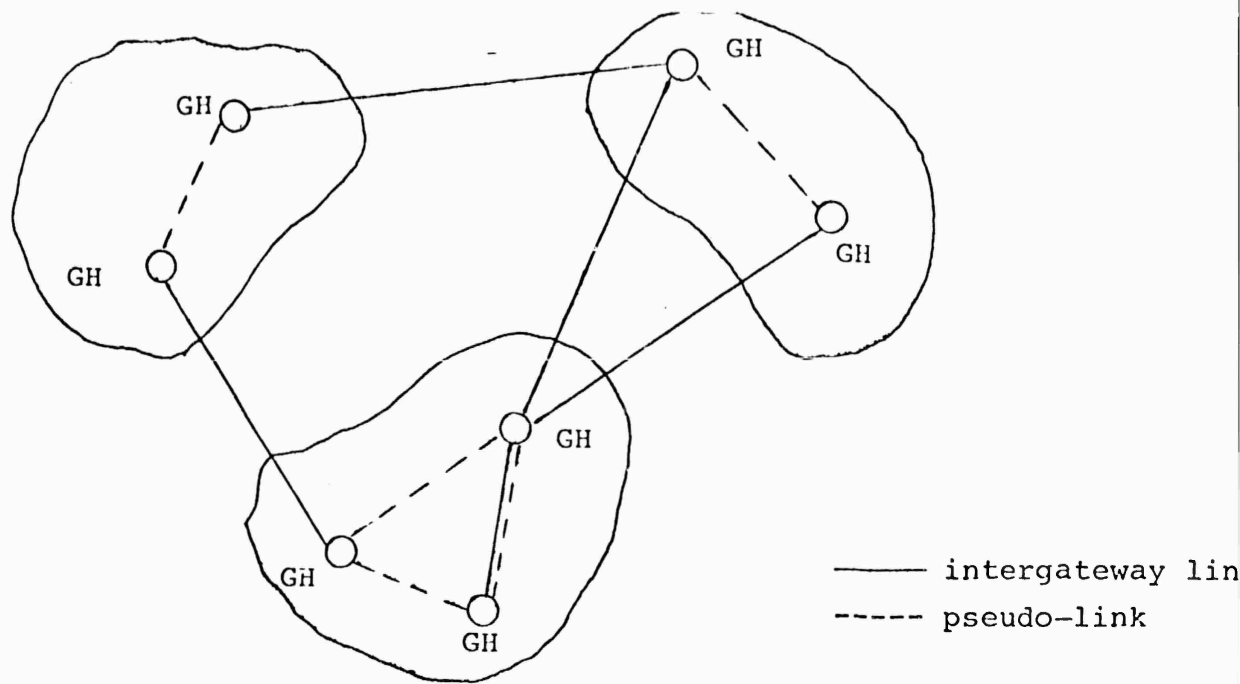


FIGURE 5: GATEWAY-HALF VIRTUAL NETWORK

Based on the local net independence principle, some general requirements for internetworking can be stated: [CERF, 1974] [SUNSHINE, 1977] [MCKENZIE, 1974]

1. The GH's should connect to the networks at the Host level (or even user level). In this way, each network can protect itself against the activities of the GH's to the same extent as it may protect itself against the activities of any other Hosts.
2. Because in general it is difficult to convert between the Host-to-Host protocols of two different networks, the GH's should communicate with nodes of the network in the lowest form of Host/node protocol supported by the network.
3. A common (international) protocol is required for Hosts desiring internetwork communication. Note that a Host may thus have to implement two sets of Host-to-Host protocols, one for its own network, and one for internetworking.
4. A uniform addressing scheme is required which can be known to all Hosts and processes participating in internetworking.
5. A common (international) packet format is required. However, within each individual network, the international traffic must appear the same as the local traffic. The common

technique used is to embed the internetwork segment inside the local packet. (See Figure 6). With suitable standardization in local packet format, the local header and the internet header can share some common segments, thus reducing the overhead [CERF, 1975].

6. Because of the difference in maximum packet size allowed in different networks, either all internetwork messages have to transmit in units of the smallest maximum size (which at present is roughly 2000 bits) or data crossing network boundaries has to be fragmented (by the GH's) into smaller pieces. Possible fragmentation schemes, are discussed in [CERF, 1974], [MCKENZIE, 1974].

7.2.3 End-to-End Protocol Issues

Several important end-to-end protocol issues which have been researched in [INWG, 1975], [CERF, 1975], [BBN, 1975], are briefly presented.

A. Fragmentation Between Gateways

As mentioned in Section 7.2.2, different networks may have different maximum packet sizes. Hence, either all internetwork traffic must be transmitted in standard size packets allowed by all networks, or some fragmentation mechanisms are required at the gateway-halves, so that messages from one network can be fragmented into smaller pieces for transmission through next network.

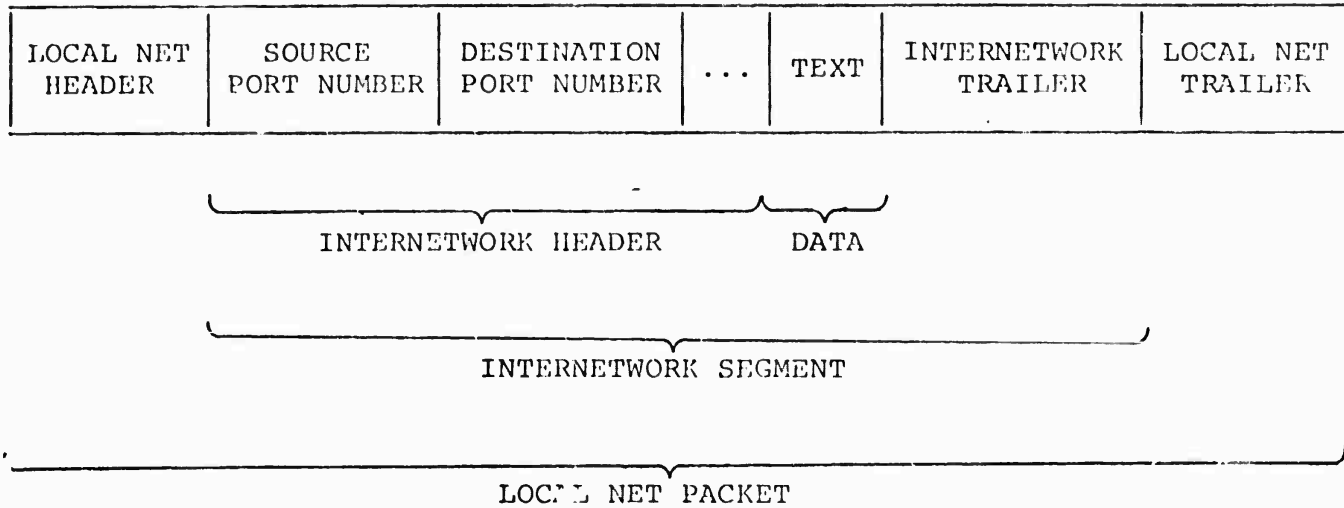


FIGURE 6: INTERNETWORK PACKET FOPMAT

Some of the arguments for fragmentation at the gateways are:

- New high speed technology and cheap memories make it attractive to use packets longer than 2000 bits in some networks, but networks built with older technology may still be limited to the smaller length.
- It is inefficient to force all networks to use only the minimum size that all networks can guarantee to carry. Moreover, it could be harmful to bind future network designs by the present technology standards.
- Encryption procedures, to function at all, may require fragmentation at the gateway.

Some of the arguments against fragmentation at the gateways are:

- Public networks will use a standard size for datagrams, and private networks will tend to adopt the same standards, at least as an option.
- Practically all current networks carry fragments at least 2000 bits in length. (However, it should be noted that in ARPANET, the maximum packet length is only 1000 bits).
- There will always be a large proportion of letters shorter than 2000 bits for transaction oriented traffic.

- Allowing longer messages or packets to improve network efficiency should not be the responsibility of the user. Rather, it should be a multiplexing scheme introduced within or at the packet switched network interface level, wherever useful (e.g., as in TYMNET and ARPANET).

It is recognized in [INWG, 1975] that if gateway fragmentation is used, a mechanism should be provided whereby the receiving transport station can specify the maximum fragment size it is willing to receive. (It may happen that the maximum packet size a transport station can handle is smaller than the maximum allowable packet size of the network it resides).

B. Flow Control, Error Control

There are several related issues:

1. Should flow control be performed on letters or on fragments?
2. Should error control be made optional?
3. Should retransmission between gateway-halves be used (possibly as an option)?

The issue of whether flow control should be done on letters or on fragments is related to both the Host buffer management and the communication link utilization. If the probability of retransmission is small, then it can be shown that the increase in link utilization using the fragment retransmission scheme over the letter retransmission scheme is rather insignificant. However, a fragment-oriented acknowledgment retransmission scheme should result in more flexible Host buffer allocation, and hence better utilization.

There is also a suggestion of using a "fragment count" on letters (thus still using a letter-based control mechanism), which should also make the buffer management more efficient.

Next, consider the issue of whether error control should be made optional. Some users may already have their own error control scheme, and thus all they need is a simple letter switching service and no network level error control is required. However, it is argued that these types of users are not common, and they probably need some flow control. Hence, for the preliminary protocol designs, it may be simpler to consider error control and flow control as a standard basic service.

Finally, consider the issue of gateway-half retransmission. The argument for gateway-half retransmission is that the source-to-destination retransmission may be quite inefficient, especially if the transmission is across several networks. It has been shown [GITMAN, 1976] that a hop-by-hop acknowledgment and retransmission scheme in addition to source-to-destination retransmission improves network efficiency, in particular when the number of hops from source-to-destination is large. These results can be applied to the analogous situation when considering ETE intranet retransmission in addition to the source-to-destination retransmission. Moreover, with gateway-half retransmission, the poor performance of one network will have less impact on the performance of other networks.

C. Checksum

The trade-off in selecting an appropriate checksum is between efficiency and reliability: A polynomial checksum provides for the protection of a wide variety of error conditions, but it is costly to compute. On the other hand, an additive type of checksum, which may be easy to compute, provides a smaller measure of protection. It should be noted that with present technology, the hardwired polynomial checksum can be produced inexpensively. Thus, the trend will probably go toward the use of polynomial checksums.

7.2.4 Gateway-Half Functional Requirements

In the following, we list the basic functions (capabilities) of gateway-halves: [BBN, 1975], [SUNSHINE, 1977].

A. Message Processing Between Two Networks

This is the most basic task a gateway-half must perform: convert traffic in the format of one network into traffic in the format of another network.

B. Inter-Gateway Routing

This issue will be discussed in Section 7.3.4.

C. Access Control Mechanisms

This function is desirable to enable a constituent network to limit some classes of traffic. Also, some users may impose a constraint on passing through some constituent network. In general, the ability of a network to monitor the use of its resources by the internetwork traffic appears to be desirable.

D. Accounting Mechanism

Some form of accounting on the internetwork traffic is clearly necessary. Various types of accounting are possible, and the gateway-halves seem to be the natural place to do it.

E. Statistics Gathering

The statistics on the performance of the gateway-halves and its host networks are important for the optimal use of the networks.

F. Internetwork Message Fragmentation

The arguments for or against message fragmentation at gateway-halves has already been elaborated upon in Section 7.2.3. At present, it seems to be a desirable option.

G. Congestion Control

This capability is especially important because of the heterogeneous nature of the networks. A particular subproblem is the congestion resulted from deadlocks.

H. Possible Inter-Gateway Retransmission

The issue related to this gateway-half capability has been discussed in Section 7.2.3.

7.3 INTERNETWORK TOPOLOGICAL DESIGN PROBLEM FORMULATION AND INTERNET ROUTING AND DESIGN ALTERNATIVES

In this section we first present a formulation of the general internetwork topological design problem. We then examine some possible alternatives in internetwork routing and topological design. Based on a selection of the alternatives, we formulate an internet routing model and the corresponding reduced topological design problem in the next two sections.

7.3.1 Internetwork Topological Design Problem Formulation

Based on discussions in Section 7.2, a formulation for the general internetwork topological design problem can be given as follows:

Given:

- Local networks that participate in intercommunication, together with their Hosts and switches.
- (Internetwork and intranetwork) traffic requirements between the Hosts.
- Facility costs/capabilities.

Optimize:

- Total communications cost D :
 $D = \text{gateway-half cost} + \text{intergateway link cost} + \text{local net link cost} + \text{local net switch costs}.$

Over the Variables:

- Number and location of the gateway-halves.
- Topology and link capacities of the local nets.
- Gateway-half virtual net topology and link capacities.

Such That:

- Traffic requirements are accommodated under suitable routing strategies.
- Average end-to-end delay constraints (may be network-pair dependent) are met.
- Other appropriate constraints (e.g., 2-connectivity) are met.

The topological design problem as stated above is very difficult to solve. For example, an internet requirement may be routed over several different networks, each with its own routing and flow control strategy. Moreover, the traffic requirement characteristics and end-to-end delay constraints may be network-pair dependent (i.e., dependent upon the originating and destination nets) and hence the routing problem is one of multiple flow classes routing over multiple non-homogeneous networks. Consequently, in this study we focus on a simplified design problem. In the remainder of this section we consider the alternatives in internet routing and topological design. Based on these considerations, we formulate a simplified internet routing problem and the corresponding topological design problem in the next two sections.

7.3.2 Internet Routing and Design Alternatives

In this subsection we examine some of the important alternatives in internet routing and topological design: route selection alternatives, route restriction alternatives, routing priority alternatives, and local net design alternatives. These alternatives form the basis of the simplified internet routing model and the basis of our experimental studies.

7.3.2.1 Route Selection Alternatives

This refers to the alternatives in selecting a route from the source Host to the destination Host. A very detailed discussion can be found in [SUNSHINE, 1977]. The issues involved are:

1. Should a fixed or an adaptive routing policy be used?
2. Should the Hosts participate in route selection?
3. Should a single level or a hierarchical routing policy be used?

In general, the adaptive routing policies are more robust and efficient than the fixed routing policies. This is especially true in the multi-network environment, because some networks are more prone to congestion and failure than the others. However, with an adaptive policy, individual node's malfunction can develop into a global catastrophe; consequently, proper safeguard must be implemented at the gateway-halves (or nodes).

Next consider the issues of Host routing. At present, Host routing is not used. However, with Host routing, each Host can be connected to several different switches, which is desirable

from a reliability point of view. From the standpoint of internetworking, Host routing is also desirable because the gateway-halves behave as Hosts. For simplicity, Host routing is not considered in this study.

Next consider the issue hierarchical levels in internet routing. With a single level routing, more efficient routes can be selected. However, this approach has two severe drawbacks. First, the routing table is necessarily very large, including all the nodes in all nets. Second, the local net routing becomes transparent to nodes in other networks, which violates the local net independence principle. With a hierarchical routing policy, in which the gateway-halves (or the switches associated with the gateway-halves) act as local "central offices," the above complications can be avoided, at the expense of some inefficiency. A message is first routed from the source Host to a gateway-half G_1 in the same network. It is then routed in the gateway-half virtual network from G_1 to a gateway-half G_2 in the destination network. (Notice that each step in the gateway-half virtual net routing represents either routing along some intergateway link, or pseudo-link, i.e., routing in a local net with the gateway-halves as source and destination "Hosts".) Finally, the message is routed in the destination network from G_2 to the destination Host. For simplicity, we assume that an internet message from (or to) a Host is always routed through its nearest gateway-half except when this gateway-half fails. Consequently, each network is partitioned by the resident gateway-halves into disjoint regions.

7.3.2.2 Routing Restriction Alternatives

There are various possible network related restrictions on the permissible routes for requirements of a particular type. The following are some of the possibilities:

A. Local Requirement Routing Restriction

Whether a requirement between Hosts of the same network can only be routed in the same local net, or can be routed through the GH virtual net and other local nets?

B. Internet Requirement Routing Restriction

Whether the internet requirements between the gateway-halves (which are induced from the Host-to-Host internet requirements) can only be routed on the intergateway links, or can be routed through local nets?

C. Network Dependent Routing Restriction

This type of restriction may take the following general form: For three networks N_1 , N_2 and N_3 , the internet requirements between Hosts in N_1 and N_2 cannot (or alternatively, must) be routed through N_3 .

In the present study, only type A and type B restrictions are considered. Specifically, we assume that the local net requirements can only be routed in the same local net; whereas the internet requirements can be routed over any nets.

The alternative of allowing local requirements to route over any net is interesting in that constraints of net boundaries do not have to be taken into account for routing. The merits of such routing is apparent when failures of links and nodes occur and when peak loads in the different networks do not occur simultaneously. This routing option is not considered in this study. Type C restrictions can be used to model many realistic constraints, however, they are difficult to apply in network design.

7.3.2.3 Routing Priority Alternatives

This issue refers to the different priorities one can assign to the different types of requirements. The following are some of the possible options:

1. Local requirements in net A (A can be any net) have (non-preemptive) priority over any other requirements using net A resources.
2. Internet requirements have priority over local requirements.
3. No priority is assigned..

7.3.2.4 Local Net Design Alternatives

In principle, when both the local requirements and the internet requirements are using the resources of a network, the local net topology and link capacities should be re-optimized to correspond to the new traffic pattern. However, this may not be allowed because of network ownership, organizational, or security reasons. The following are the possible alternatives:

1. Both the local net topologies and the link capacities are fixed.
2. The local net topologies are fixed, but the link capacities can be modified.
3. The local net topologies are allowed to be modified.

7.4 A SIMPLIFIED INTERNET ROUTING MODEL

In one context, the internet routing problem is that of routing the local requirements in their respective local nets, and routing the internet requirements over all the local nets and inter-gateway links, subject to the following delay constraints:

1. Average end-to-end delay constraints for the intranetwork requirements (can be different for different nets);
2. Average end-to-end delay constraints for the internetwork requirements between a pair of nets (can be different for different pairs of nets).

Similar to the single network - single packet flow class case, one can develop simple approximate expressions for the average end-to-end delays in the multi-network context. For local nets A, B and (local or intergateway) link ℓ , let

$f_{A,B}(\ell)$ = total flow (bits/sec) on link ℓ due to requirements between Hosts in network A and Hosts in network B,

$T_{A,B}(\ell)$ = average packet delay (sec/packet) of $f_{A,B}(\ell)$ on link ℓ ,

and

$\gamma_{A,B}$ = total requirements (bits/sec) between Hosts in network A and Hosts in network B.

Then the average end-to-end delay for $\gamma_{A,B}$ is given by;

$$T_{A,B} = \frac{1}{\gamma_{A,B}} \sum_{\text{all links}} f_{A,B}(\ell) T_{A,B}(\ell) \quad (1)$$

The derivation is similar to [KLEINROCK, 1972].

On each link ℓ , there may be many flow groups $f_{A,B}(\ell)$ present, and the average delay experienced on link ℓ by each flow group is dependent upon the interaction of all the flow groups on ℓ . Moreover, each local net may have distinct routing and flow control strategies. Consequently, performance (i.e., end-to-end delay) evaluation is a very difficult problem in this multi-flow, multi-network context. Equation (1), which is simple in appearance, in practice is difficult to evaluate.

To alleviate the difficulty, we formulate a simplified internet routing model with the following assumptions:

1. Each Host is connected to a unique switch.
This assumption simplifies the routing problem to that of routing between the switches.
2. Local requirements are routed only within the same local net.
3. The gateway-halves are responsible for internet routing. A gateway-half virtual net routing table is stored at each gateway-half. The routing table is maintained and updated in the same manner as the single net routing table. This approach allows better internet management, local net independence and growth flexibility.
4. The acknowledgment scheme in the gateway-half virtual network is hop-by-hop. (Thus, for two gateway-halves in the same local net, the internet acknowledgment on the "pseudo-link" appears

as end-to-end acknowledgment in the local net.)

5. The gateway-halves in the same local net partition the network into disjoint regions. Each gateway-half serves as a local internet routing center for the switches in its region. However, when the regional gateway-half is inoperative the internet traffic is routed through a neighboring gateway-half.
6. For simplicity, each gateway-half resides in a switch. Thus, conceptually we can identify a gateway-half with the switch it resides in.

Under these assumptions, the routing of an internet message is carried out in three steps:

1. Local net routing from the source switch (or Host) to the source regional gateway-half.
2. Gateway-half virtual net routing from the source regional gateway-half to the destination regional gateway-half.
3. Local net routing from the destination regional gateway-half to the destination switch (or Host).

Based on the above routing model, the original local and internet traffic requirements between the Hosts (in the same or in different nets) can be re-grouped into the following three classes:

1. Local requirements between switches in the same local net corresponding to the original local requirements;
2. Local requirements between switches and their regional gateway-halves induced by the internet requirements;
3. Internet requirements between the gateway-halves in different nets induced by the internet requirements.

We call the above three types of requirements: local switch to switch, local switch to gateway-half, and internet gateway-half to gateway-half requirements.

Corresponding to the routing model and the resulting traffic requirement partition introduced in Section 7.4.1, we can consider three types of delay constraints:

1. Local net average end-to-end delay constraint for the local net switch-switch requirements (can be different for different nets);
2. Average switch to gateway-half delay constraint for the local net switch-gateway half requirements (can be different for different nets);
3. Average end-to-end delay constraint for the internet gateway-half to gateway-half requirements in the gateway-half virtual net.

By setting the second type (switch to gateway-half) constraints appropriately, we can model the more general average end-to-end delay constraints between different network pairs. (Admittedly this modeling is imperfect.) Notice that the first two types of constraints (and corresponding flows) are local, and consequently the routing and delay evaluation can be done for each local net separately. The only interaction is between the internet gateway-half to gateway-half flow and the local flows in each local net. The complexity of the problem is thus significantly reduced.

7.5 A SIMPLIFIED INTERNETWORK TOPOLOGICAL DESIGN PROBLEM AND SOLUTION APPROACH

Based on the internet routing model developed in Section 7.4, we formulate a simplified internet topological design problem. A heuristic solution approach based on extensions of existing topological design techniques is also proposed. Finally, a heuristic procedure for selecting the gateway-halves is presented.

7.5.1 Formulation of the Internetwork Topological Design Problem

Based on the discussions in the last section, we modify the internetwork topological design problem given in Section 7.3.1 to be as follows:

GIVEN:

- Local networks that participate in internet communication, together with their switches.
- (Internetwork and intranetwork) traffic requirements between the switches.
- Facility costs/capabilities.

OPTIMIZE:

Total communications cost D :

$D = \text{gateway-half cost} + \text{intergateway link cost} + \text{local net link cost} + \text{local net switch cost}.$

OVER THE VARIABLES:

- Number and location of the gateway-halves.
- Topology and link capacities of the local nets. (This may not be allowed as a variable.)
- Gateway-half virtual net topology and link capacities.

SUCH THAT:

- Traffic requirements are accommodated (under suitable local net and gateway-half virtual net routing strategies).
- Average end-to-end delay constraints (local switch to switch, local switch to gateway-half, internet gateway-half to gateway-half) are met.
- Other appropriate constraints (e.g., 2-connectivity) are met.

7.5.2 A Solution Approach for the Internet Topological Design Problem

Topological design is in general a very difficult problem, even in the case of a single network. Consequently, an effective exact solution procedure for the internetwork topological design problem formulated in Section 7.5.1, appears unlikely. However, based on ex-

tensions of existing design techniques for a single network, good heuristic solution approaches are possible. One approach is as follows:

- Step 1. Find a set of "good" gateway-half locations (based on internet cost tradeoff considerations).
- Step 2. For each network, based on the gateway-halves chosen, partition the switches into disjoint sets.
- Step 3. Determine a "good" internetwork topology (i.e., local net topologies and inter-gateway connections).
- Step 4. For each local net, determine the link capacities and the routes for the local (type 1(a) and type 1(b)) requirements so that the respective delay constraints are satisfied. Also, determine the average delay and average incremental delay between each pair of gateway-halves in the same net (which corresponds to the average delay and average incremental delay on the gateway-half pseudo-links).
- Step 5. Determine the intergateway link capacities so that the delay constraints for the type 3 (internet gateway-half to gateway-half) requirements are satisfied in the gateway-half virtual net.

Step 6. Based on the internet flow assigned to the pseudo-links (which corresponds to additional requirements between the gateway-halves in the same local net), route the internet flow onto the local links. Re-evaluate the delay for the local requirements.

Step 7. If the stopping criteria (e.g., number of iterations or network cost differences between iterations) are satisfied, then stop; otherwise, go to Step 3.

Several remarks are in order. First, the above approach allows each local net to have a different routing and network design strategy. Second, if the local net topologies (and capacity) are not allowed to change, then in Step 3, only the intergateway links are selected. Third, in the above approach, the local net routing is done before the internet routing. This is based on the assumption that due to the local net independence principle, it is more important to accommodate the local requirements in the respective local nets, especially if the local net topologies are not allowed to change. (The internet requirements can always be satisfied by adding more gateway-halves and more links between the gateway-halves). Finally, note that it is possible for the local end-to-end delay to exceed the constraint after Step 6. In all of our design experiments, only a small amount of internet gateway-half to gateway-half requirement is routed on the local links, hence this problem does not occur. Moreover, the routing of intergateway requirements in local nets can be constrained so that the amount of internet flow placed on the local links will never cause the local net end-to-end delay constraints to be violated.

Step 1 of the solution approach, the selection of the gateway-half locations, will be discussed in Section 7.5.3. In order to avoid excessive running time, we assume that the gateway-halves are co-located with the switches (i.e., the switch locations form the set of gateway-half location candidates). Steps 3 through 6 of the internet topological design procedure can be carried out by applying single network routing and topological design techniques (e.g., [GERLA, 1977], [BOORSTYN, 1977], [CANTOR, 1974], [MARUYAMA, 1976a], [MARUYAMA, 1976b]) to the local nets and the gateway-half virtual nets. A description of some of the network design strategies is given in Chapter 3 of this semiannual report.

7.5.3 Gateway-Half Selection Procedure

In this subsection we consider the problem of selecting the gateway-half locations for internetworking. We present an effective solution procedure, based on extensions of solution techniques for the backbone switch location problem [NAC, 1976a] and the satellite switch location problem [NAC, 1976b].

7.5.3.1 Procedure Development

For any switches a, b in the same local net, let

$CL(a,b)$ = average cost of transmitting a unit traffic requirement from a to b through the local net.

Also, for gateway-halves G_1, G_2 , let

$CI(G_1, G_2)$ = average cost of transmitting a unit traffic requirement from G_1 to G_2 through the gateway-half virtual net.

Let Q be a gateway-half candidate in local net N_1 . We examine the cost tradeoffs involved in using Q as a gateway-half. (By assumption, Q is co-located with one of the switches in N_1 .) In the equations that follow, G denotes a gateway-half. Let a be a switch in N_1 and G_a its associated gateway-half. Let N_2 be any other local net, b a switch in N_2 , and G_b the gateway-half associated with b . The cost of transmitting a unit requirement from a to b is (see Figure 7):

$$C(a,b) = CL(a,G_a) + CI(G_a,G_b) + CL(G_b,b). \quad (2)$$

If Q is used as a gateway-half, and a is assigned to Q , then the cost for transmission becomes;

$$\bar{C}(a,b) = CL(a,Q) + CI(Q,G_b) + CL(G_b,b) \quad (3)$$

The cost difference of assigning a to Q , relative to the (a,b) pair, is thus:

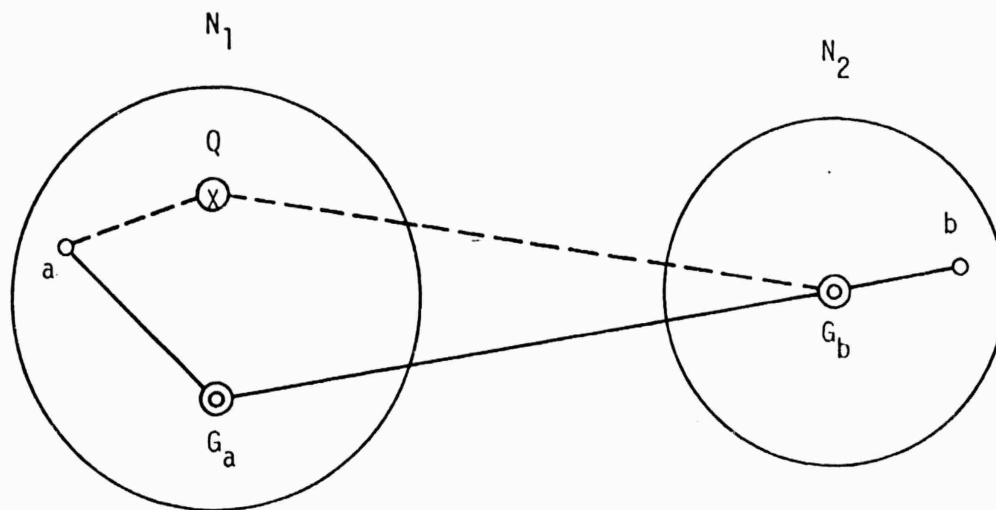
$$S(Q,a,b) = [CL(a,G_a) - CL(a,Q)] + [CI(G_a,G_b) - CI(Q,G_b)]. \quad (4)$$

For a gateway-half G not in N_1 , let

$t(a,G)$ = traffic requirements between switch a and switches associated with G .

$t(a)$ = total internet traffic requirement of switch a .

Then by Equation (4), the saving of assigning a to Q is;



G_a GATEWAY-HALF

Q GATEWAY-HALF CANDIDATE

a SWITCH

FIGURE 7: GATEWAY-HALF LOCATION TRADEOFFS

$$\begin{aligned}
 S(Q,a) &= \sum_{G \in N_1} t(a,G) \{ [CL(a,G_a) - CL(a,Q)] + [CI(G_a,G) - CI(Q,G)] \} \\
 &= t(a) [CL(a,G_a) - CL(a,Q)] + \sum_{G \in N_1} t(a,G) [CI(G_a,G) - CI(Q,G)].
 \end{aligned}
 \tag{5}$$

For ease of computation, we approximate $t(a,G)$'s by;

$$t(a,G) \approx t(a) \times \frac{t(G)}{tI(N_1)}, \tag{6}$$

where;

$t(G)$ = total internet traffic for switches associated with gateway-half G ,

$tI(N_1)$ = total internet traffic to and from all nets other than N_1 .

Substituting Equation (6) into Equation (5), we obtain;

$$\begin{aligned}
 S(Q,a) &= \frac{t(a)}{tI(N_1)} \{ tI(N_1) \times [CL(a,G_a) - CL(a,Q)] \\
 &\quad + \sum_{G \in N_1} t(G) \times [CI(G_a,G) - CI(Q,G)] \}
 \end{aligned}
 \tag{7}$$

The total saving of using Q as a gateway-half is thus;

$$S(Q) = \sum \{ S(Q,a) \mid a \in N_1, S(Q,a) > 0 \} - C_{GH}(Q), \tag{8}$$

where

$C_{GH}(Q)$ = gateway-half cost at Q .

With the savings for each gateway-half candidate determined by Equation (8), the gateway-halves can be selected using an ADD-type iterative procedure (i.e., the gateway-half candidate with the largest positive saving is selected as the next gateway-half [NAC, 1976a]. The only remaining task is to estimate the unit transmission cost for the local nets and the internet (i.e., the $CL(a,b)$'s and the $CI(G_1, G_2)$'s).

7.5.3.2 Unit Transmission Cost Estimate

As shown in Section 7.5.3.1, the optimal gateway-half location strategy is the result of the tradeoffs between the local net access cost and the internet cost. In principle, the most accurate way to select the optimal set of gateway-halves is to evaluate the total system cost, by procedures such as the one outlined in Steps 2-6 of Section 7.5.2, for each candidate set of gateway-halves. This process, however, is too time consuming to be of practical value. The alternative is to have a simple, yet effective way to estimate local net and gateway-half virtual net transmission costs associated with a set of gateway-halves. This is the approach taken in the backbone transmission cost evaluation for selecting the backbone switches or the satellite switches [NAC, 1976a], [NAC, 1976b].

As shown in [NAC, 1976a], for a given set of backbone switches, the transmission cost for a unit of requirement between two switches a and b can be effectively estimated by:

$$\begin{aligned} U(a,b) &= C_T \times Pxd(a,b) \times \frac{1+b}{\rho} + C_H \times \frac{Pxd(a,b)}{D} \times \frac{1+b}{\rho} \\ &= (C_T + \frac{C_H}{D}) \times Pxd(a,b) \times \frac{1+b}{\rho}, \end{aligned} \quad (9)$$

where

C_T = average trunk line cost/unit bandwidth/mile/month.

C_H = average trunk line termination cost (both ends)/month.

D = average link mileage.

P = non-direct routing factor (ratio of average shortest path length to direct distance).

d(a,b) = direct distance between a and b.

b = average protocol overhead.

ρ = average link utilization.

Notice that on the right-hand-side of Equation (9), the first term, $C_T \times P \times d(a,b) \times \frac{1+b}{\rho}$, gives an estimate on the line mileage cost per unit requirement between a and b; the second term, $C_H \times \frac{P \times d(a,b)}{D} \times \frac{1+b}{\rho}$, gives an estimate on the line termination cost per unit requirement between a and b. The coefficients C_T and C_H are determined by the facility cost/capacity options; b is determined from the traffic characteristics and network technology; D, P, and ρ are determined experimentally. Experimental results indicate that for a given data base, and a reasonable set of switch locations, the values for P and ρ are fairly stable.

One can similarly estimate the unit transmission cost in the gateway-half virtual net. One thus obtains;

(1) For each local net N, and switches a, b in N,

$$CL_N(a,b) = (C_T(N) + \frac{C_H(N)}{D(N)}) \times P(N) \times d(a,b) \times \frac{1+b(N)}{\rho(N)} \quad (10)$$

where the functional representation $C_T(N)$, $C_H(N)$, etc., indicate that these parameters are functions of the local net N;

(2) For the gateway-half virtual net, and gateway-halves G_1, G_2 ,

$$CI(G_1, G_2) = (C_T(V) + \frac{C_H(V)}{D(V)}) \times P(V) \times d(G_1, G_2) \times \frac{1+b(V)}{\rho(V)} \quad (11)$$

where V is used to represent the gateway-half virtual net.

7.5.3.3 Extension to Modularized Gateway-halves

Notice that in the basic procedure described in Section 7.5.3.1, one gateway-half is selected at a time. However, one can also regard this procedure as selecting one gateway-half module at a time. Thus, during the ADD selection process, once a switch is assigned to a selected gateway-half module, it is deleted from consideration, but the location corresponding to the selected gateway-half module can still be used as a candidate, and compete for other switches. Moreover, the module cost for a location can be made to be a function of the number of modules already selected at that location. (The interpretation of C_{GH} in Equation (8) is now the gateway-half module cost.) In this way, the cost/capacity model can be made more realistic.

7.6 EXPERIMENTAL RESULTS

The procedures presented in Section 7.5 have been implemented on a PDP-10. Numerous experiments were performed to study cost/performance tradeoffs in interconnection of packet switched networks. The following two data bases were used:

1. A model data base with 4 networks, each having 8 switches.
2. ARPANET and a simplified version of AUTODIN II.

In this section we first briefly describe the internetwork design programs developed. We then examine the experimental results on the 4-net sample data base, and on the ARPANET-AUTODIN II data base.

7.6.1 Program Development

A version of the internetwork routing and topological design procedure described in Section 7.5.2 has been implemented on a PDP-10, using the Rational Fortran language. This program is based on the existing single network, single packet flow class network design program systems at NAC. Program modifications were required because of the following reasons:

1. Instead of only one class of flow, two classes of flows are present at all times. In the routing of the local requirements for a local net N, the internetwork requirements are also present as "fixed" or "passive" flows (i.e. the internet flow may be present in a local net link, but is not modifiable during the local net design phase), while

the local requirements are the "active" flows (i.e., the routing optimization is done on the local flow patterns). In the routing of the internet requirements between the gateway-halves in the gateway-half virtual net, the flow corresponding to the internet requirements are the "active" flows, while the flows corresponding to the local requirements (for all the local nets) are the "fixed" or "passive" flows.

2. Program I/O capabilities had to be extended to accommodate several network files (one for each local net, plus one for the gateway-half virtual net). Depending upon the user's command, one of these network files will be brought in for processing.

Similar to the single network design system, this internetwork design program is interactive: The routing optimization is done automatically, but the topology selection is done through the user-program interaction.

A version of the internetwork gateway-half selection procedure has also been implemented on a PDP-10 using the Rational Fortran language. Upon entering the data base of nets and their associated switches, and the appropriate cost and utilization parameters, the program will select the gateway-half locations (at least one in each local net), and assign each switch to its nearest gateway-half in the same local net. The resulting data base of gateway-halves and switches can then be used by the internetwork design program to obtain the actual line layout, capacity assignment and flow assignment.

An auxiliary program was also developed to set up the appropriate traffic matrix for the internetwork design program. The inputs to this program are;

1. Original (internetwork and intranetwork) traffic requirements between the switches,
2. Location file of the switches and the gateway-halves, together with the switch to gateway-half association. The latter is obtained from the gateway-half selection program.

The outputs of this program are:

1. For each local net, the local traffic requirements between the switches. This is the sum of the local switch-switch requirements and the local switch to gateway-half requirements. (Notice that we assume the gateway-halves are co-located with the switches.)
2. For the gateway-half virtual net, the internet requirements between the gateway-halves.

7.6.2 Interconnection of a Model 4-Network Data Base

7.6.2.1 Assumptions on the Model Data Base

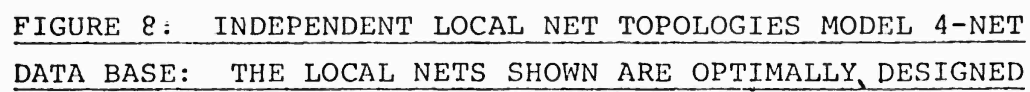
To study the general behavior of network interconnection, we constructed a model data base with the following characteristics:

Number of networks	= 4
Number of switches	= 32 (8 in each net)
Total data traffic requirements	= 5 Mbps
Average data packet text portion size (same for all nets)	= 740 bits
Local net packet header size (same for all nets)	= 110 bits
Internet packet header size	= 100 bits
RFNM (Request for Next Message) packet size (same for all nets)	= 150 bits
Number of RFNM packet/data packet (same for all nets)	= 1
Local link routing overhead (same for all nets)	= 7%
Intergateway link routing overhead	= 7%

Notice that for simplicity, we assume that all the local nets have the same packet header size, RFNM packet size, routing overhead, etc. The packet header size and the RFNM size are believed to be representative of the current ARPANET technology. The networks, the interconnection of which are studied in this section, are of equal size in terms of number of nodes and throughput; they differ in topology and node locations. This example was purposely constructed for studying properties and tradeoffs in interconnecting "similar" networks, in contrast to the case of interconnecting ARPANET and AUTODIN II.

The geographical distribution of the networks is as shown in Figure 8. The 4 networks approximately span the continental United States. Each network covers a distinct area, with some slight overlapping.

From the information given above, we can evaluate the average packet length and the average protocol overhead for the local packets and the internet packets in either the local nets or internet (i.e., gateway-half virtual net).



In deriving the average packet length for the experiments we considered only information packets and RFNM's. The average protocol information was derived using packet header and text length and RFNM's; other protocol packets were not taken into account. [NAC, 1975].

Local Packets in Local Nets

The local packets refer to the data packets for the original local switch-switch requirements. For this traffic we obtained:

$$\begin{aligned} \left(\begin{array}{c} \text{average protocol} \\ \text{overhead} \end{array} \right) &= 35\% \\ \left(\begin{array}{c} \text{average packet} \\ \text{length} \end{array} \right) &= 500 \text{ bits} \end{aligned}$$

Local Packets in Intergateway Links

By Assumption 2 in Section 4.1, this option is not allowed.

Internet Packets in Local Nets

The internet packets refer to the data packets for the original internet switch-switch requirements. In this case, for each data packet, both local and internet headers are required. This results:

$$\begin{aligned} \left(\begin{array}{c} \text{average protocol} \\ \text{overhead} \end{array} \right) &= 49\% \\ \left(\begin{array}{c} \text{average packet} \\ \text{length} \end{array} \right) &= 550 \text{ bits} \end{aligned}$$

Internet Packet in Intergateway Link

In this case, the only packet header is the internet packet header. The average protocol overhead and packet length are:

$$\left(\begin{array}{c} \text{average protocol} \\ \text{overhead} \end{array} \right) = 34\%$$

$$\left(\begin{array}{c} \text{average packet} \\ \text{length} \end{array} \right) = 495 \text{ bits}$$

We make the following assumptions on the traffic requirement distribution:

1. The total internetwork and intranetwork traffic level requirement is constant, at 5 Mbps. The internet communication only impacts upon the available communicating Hosts, and upon the contributions from the available communicating Hosts (i.e., more local traffic implies more contributions from the Hosts in the same local net).
2. The local traffic for a local net is distributed uniformly among the local switch pairs (i.e., pair of switches a and b such that both a and b are in the same local net). Each local net has equal amount of local traffic requirement.
3. The internet traffic is distributed uniformly among all the internet switch pairs (i.e., pair of switches a and b such that a, b are in different local nets).

Table 1 lists the costs and capabilities of the line and hardware options used in the internet and local net designs. Notice that modular architecture is assumed for the gateway-halves, i.e., more than one gateway-half module can be used at the same location. The trunk line costs/capabilities are based on the AT&T Telpak

<u>FACILITY TYPE</u>	<u>CAPACITY</u>	<u>COST</u>
<u>Trunk Line</u>		
Mileage cost		\$5/mile/month
Fixed cost (both ends)		\$850/month
Data rate	50 Kbps	
<u>Switch</u>		
Unit cost		\$10.6K/month
Software development cost		\$60K/month (for all switches)
Number of high speed I/O lines	25	
Number of low speed I/O lines	100	
Total throughput (Host+terminal+S/F)	1750 Kbps	
<u>Gateway-Half Module</u>		
Unit cost		\$2K/month
Software development cost		\$15K/month (for all gateway-halves)
Number of high speed I/O lines	7	
Total throughput	200 Kbps	

TABLE 1: FACILITY COSTS AND CAPABILTIES; FOR THE 4-NET DATA BASE

offerings. The switch costs/capabilities are based on the estimated BBN Pluribus IMP's. The gateway-half module costs/capabilities are based on the ARPANET IMP-like minicomputers.

7.6.2.2 Design Results on the Model Data Base

We first consider the situation when there is no internet traffic and design each local net based only on the local traffic requirement. In this case, each local net has 1.25 Mbps traffic requirements. We design each net optimally (based on 200 msec. average end-to-end delay constraint). The resulting network configurations are shown in Figure 8. The total system cost is approximately \$841K/mo. (see Table 2). Usually, local networks will be operational and designed without consideration of internetworking.

Next, we consider the case when there is 1 Mbps of internet traffic requirements distributed uniformly among all the pairs of switches (a,b), where a, b are in different local nets. (Each local net thus has 1 Mbps of local requirements between switches in the same local net). The gateway-half selection procedure was applied to determine the optimum number and location of gateway-halves under different cost parameters. From among the solutions we selected the following two sets for tradeoff studies: one set has 4 gateway-halves, with one gateway-half in each local net; the other set has 8 gateway-halves, with 2 gateway-halves in each local net. The internet and local net topologies are then designed for each set of gateway-halves based on the procedure presented in Section 7.4.2. The results are shown in Figures 9 and 10. The cost for the 4-gateway-half system is approximately \$1039K/mo., while the cost for the 8-gateway-half system is approximately \$1083K/mo. (see Table 2).

Interestingly, we found during the design experiments that if the local nets are not allowed to be modified, then the internet requirements cannot sometimes be accommodated in the local nets.

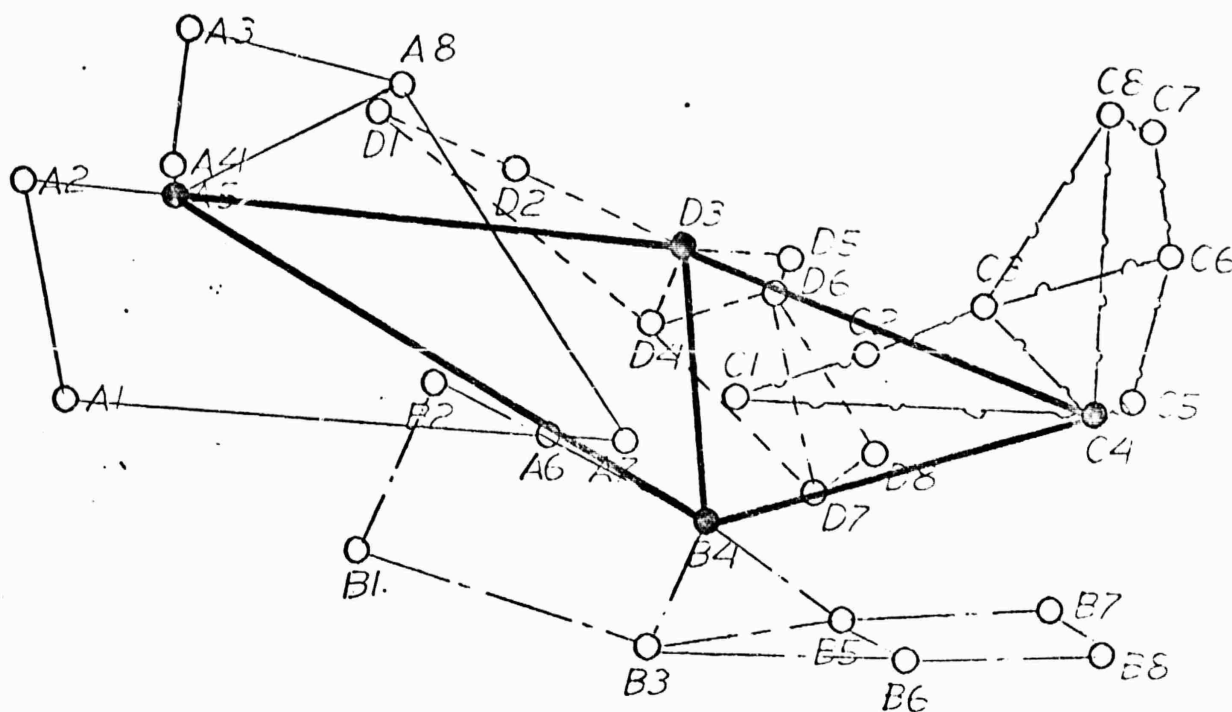


FIGURE 9: INTERNET TOPOLOGY WHEN EACH NET HAS ONE GATEWAY-HALF
MODEL 4-NET DATA BASE; 1-Mbps INTERNET REQUIREMENTS

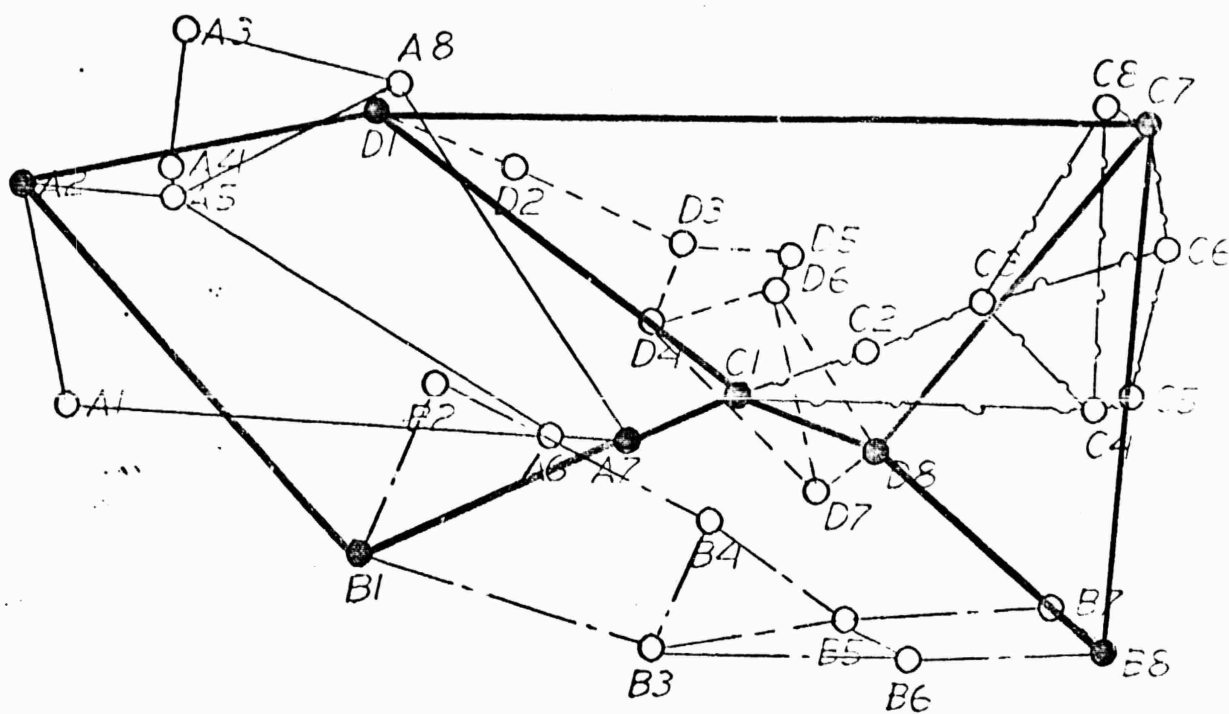


FIGURE 10: INTERNET TOPOLOGY WHEN EACH NET HAS TWO GATEWAY-HALVES
MODEL 4-NET DATA BASE; 1-Mbps INTERNET REQUIREMENTS

Internet Traffic	0	1 Mbps	1 Mbps	2 Mbps	2 Mbps
Local Net Traffic	1.25 Mbps/net	1 Mbps/net	1 Mbps/net	.75 Mbps/net	.75 Mbps/net
# of GH's Used	0	4(1 per net)	8(2 per net)	4(1 per net)	8(2 per net)
Total Channel cost for net 1	\$121.5K/mo.	\$131.8K/mo.	\$125.1K/mo.	\$145.9K/mo.	\$145.4K/mo.
Total Channel cost for net 2	116.1	132.7	123.8	140.4	134.5
Total Channel cost for net 3	108.9	117.2	110.2	128.5	124.4
Total Channel cost net 4	95.5	107.1	100.3	124.6	118.6
Total Intergateway channel cost	0	111.8	185.6	193.3	298.3
Total switch cost	399.2	399.2	399.2	399.2	399.2
Total GH cost	0	39.0	39.0	55.0	63.0
TOTAL COST	\$841.2K/mo.	\$1,038.8K/mo.	\$1,083.2K/mo.	\$1,186.9K/mo.	\$1,283.4K/mo.

TABLE 2: COMPONENT COSTS OF DESIGN RESULTS - MODEL 4-NET DATA BASE

This leads to the following observation.

Observation 1. For each local net, if less than half of the switches are gateway-halves, then the local net link capacities must be increased in order to accommodate the local net traffic resulting from the type 2 (i.e., switch to gateway-half) traffic requirements.

This observation can be explained by the following simple calculation. There is 1 Mbps of internet requirement, and 4 nets. Consequently, each local net has $(1 \times 2)/4 = .5$ Mbps internet requirements. Under the assumption of uniform traffic distribution, this implies that each switch has 62.5 Kbps internet requirement. Suppose gateway-halves are installed at less than half of the switch locations, i.e., there are at most 3 gateway-halves in each net, then the internet requirements for the remaining switches in the same net generate at least $(8-3) \times 62.5 = 312.5$ Kbps of local net requirement. The total local net requirement, excluding the overhead, is thus at least 1312.5 Kbps (1 Mbps of original local requirement plus the 312.5 Kbps internet requirement). The local net link capacities were originally sized only to handle 1250 Kbps of local net requirement. Hence more capacity is needed.

Observation 1 implies that if the local nets are not allowed to be modified, then a large number of gateway-halves are needed, which may not be desirable.

We have attempted to modify the local net topologies to improve overall internet cost. However, very little cost improvement is achieved. In fact, we were only able to improve network 1 cost by about 5%, and unable to improve other nets at all. This leads to the following observation.

Observation 2. Modifications on the local net link capacities are sufficient to produce a good global design. Hence, topological modifications on the local nets are not necessary.

This observation can be partially explained as follows:

- (a) In the design example considered, for each local net, the local switch-switch traffic dominate over the local switch-gateway-half traffic. Consequently, the change in the pattern of traffic requirement distribution is not drastic, which may imply that the original topology is still adequate for the perturbed traffic distribution pattern.
- (b) The traffic requirements are distributed and the routing algorithm is adaptive; which implies a certain degree of insensitivity of the network topology (and many other properties) to perturbations in the traffic requirement pattern.

Next, we increase the internet requirements to 2 Mbps, and reduce the intranet requirements for each local net to 750 Kbps. Internet design procedures were then applied to the 4-gateway-halves set and the 8-gateway-halves set. The cost results are entered in Table 2. The cost for the 4-gateway-halves system is approximately \$1187K/mo., while the cost for the 8-gateway-halves system is approximately \$1283K/mo. Again, Observations 1 and 2 hold.

Comparing all the design results listed in Table 2, we make the following observations:

Observation 3. With the total requirement level fixed, the higher the proportion of internet requirement, the higher the total system cost.

Observation 3 is somewhat intuitive, because the internet requirements usually use more total system resources than the local requirements. If the local nets are not allowed to change, then Observation 3 is trivially true. What we have demonstrated is that even when the local nets are allowed to be re-optimized, the internet requirements are still more costly than the local requirements.

Observation 4. For a fixed level of internet and intranet requirements, more gateway-halves leads to a higher total system cost.

Examining the component costs, one finds that with more gateway-halves:

- (a) The gateway-half link cost increases significantly,
- (b) The link cost for each local net reduces slightly,
- (c) The gateway-half module cost increases slightly.

Consequently, the increase in total system cost when more gateway-halves are used is due mainly to the increase in the gateway-half link cost.

Observation 4 can be explained by the following facts on the model data base:

- (a) The local nets are more or less regionalized. Thus, the access cost from the switches to the associated gateway-half is usually small in comparison to the gateway-half to gateway-half communication cost.
- (b) The internet traffic requirement is distributed uniformly among all the switch pairs. Consequently, for any selection of the gateway-half set, there is usually comparable direct traffic requirements between any pair of gateway-halves. Thus, more gateway-halves used implies a much more costly gateway-half virtual network.

Before changing the subject, we make two final remarks on Observation 4:

- (a) Notice that the gateway-half module cost constitutes only a very small part of the total system cost. Consequently, changes in the relative cost between communication channels and the gateway-half modules have only minor impact on Observation 4.
- (b) In the model data base very powerful switches (Pluribus-IMP type) are used and the unit switch cost is fixed. Consequently, the switch cost does not enter into the trade-offs on the different number of gateway-halves. If the switches are modularized, and each module is much less powerful, then

the switch cost will impact upon the trade-offs. In general, fewer gateway-halves implies more switch to gateway-half traffic in the local net, and hence higher switch cost. However, the general trend appears to be that the hardware costs reduce at a faster rate than the communication costs. Consequently, the communication cost would dominate over the hardware cost.

Finally, to find the cost differences between a local nets-internet system and a fully integrated system, we design a fully integrated packet-switched network on the 32 switches, based on the 4 Mbps of "local requirements" and the 1 Mbps of "internet requirements", and the 200 msec. average end-to-end delay constraint. The resulting topology is shown in Figure 11. Assuming that no internet protocol overhead is needed, the total cost for the integrated system is \$943.5K/mo. Comparing with the 8-gateway-halves system, the cost difference amounts to only 15% of the fully integrated system cost. However, the 8 gateway-halves system allows each local net to maintain its independence. This leads to the following observation.

Observation 5. The cost for an interconnected system is of the same order as an integrated system on the same set of switches.

We thus conclude that network interconnection is an effective strategy for merging several divergent packet-switched networks.

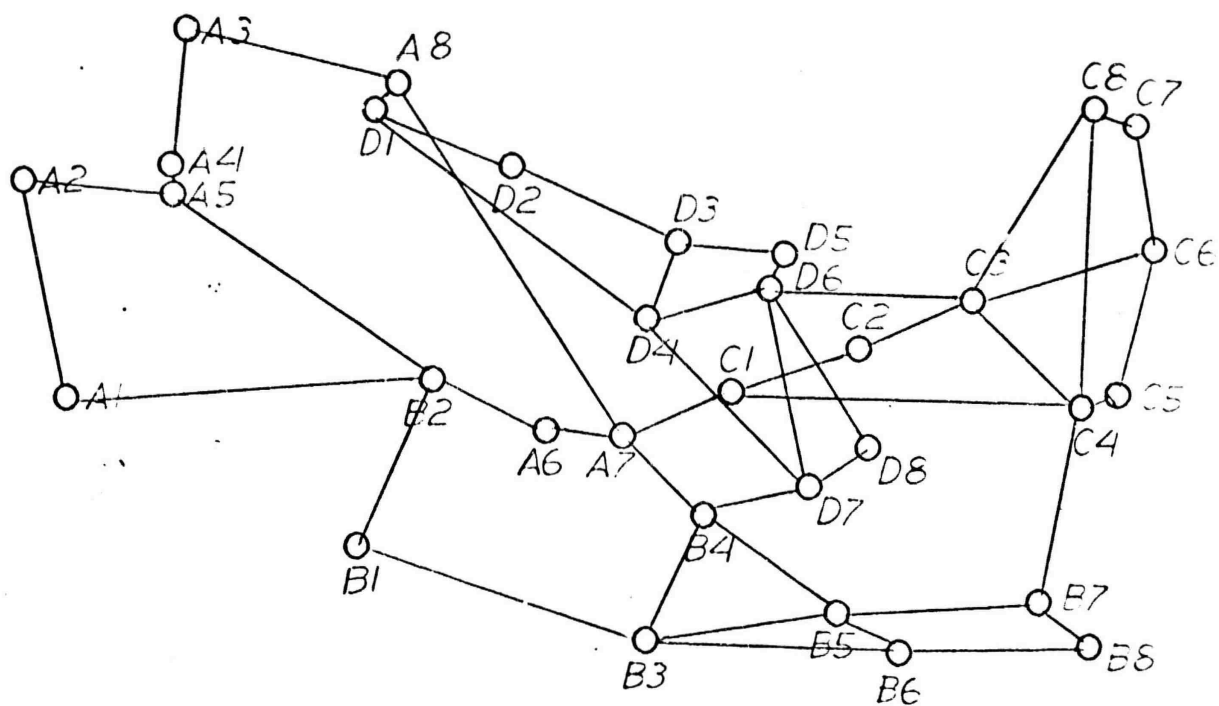


FIGURE 11: TOPOLOGY OF A FULLY INTEGRATED NETWORK ON THE
32 SWITCHES MODEL 4-NET DATA BASE

7.6.3 Interconnection of ARPANET-AUTODIN II Backbone Network

7.6.3.1 Assumptions on the Data Base

ARPANET

For this study, we use the ARPANET statistics described in [NAC, 1975]. The network configuration is as shown in Figure 12. This configuration includes all the nodes installed or planned for immediate installation as of May, 1975. The traffic requirement distribution is based on information collected at BBN and UCLA between May 1974 and February 1975. Due to its slow growth, we feel that the conclusions drawn from the 1975 ARPANET should be equally applicable to the current ARPANET.

The ARPANET characteristics are summarized as follows:

Number of switches	=	54
Total data traffic requirement (peak hour)	=	57.0 Kbps
Average data packet text portion length	=	600 bits
Maximum data packet text portion length	=	1000 bits
Packet header size	=	150 bits
RFNM packet size	=	150 bits
Average number of RFNM packets/data packet	=	1
Routing overhead	=	7%

AUTODIN II

For the AUTODIN II, we used a simplified model of an 8-node backbone packet-switched network. The network configuration is as shown in Figure 13. Summary of AUTODIN II characteristics are as follows:

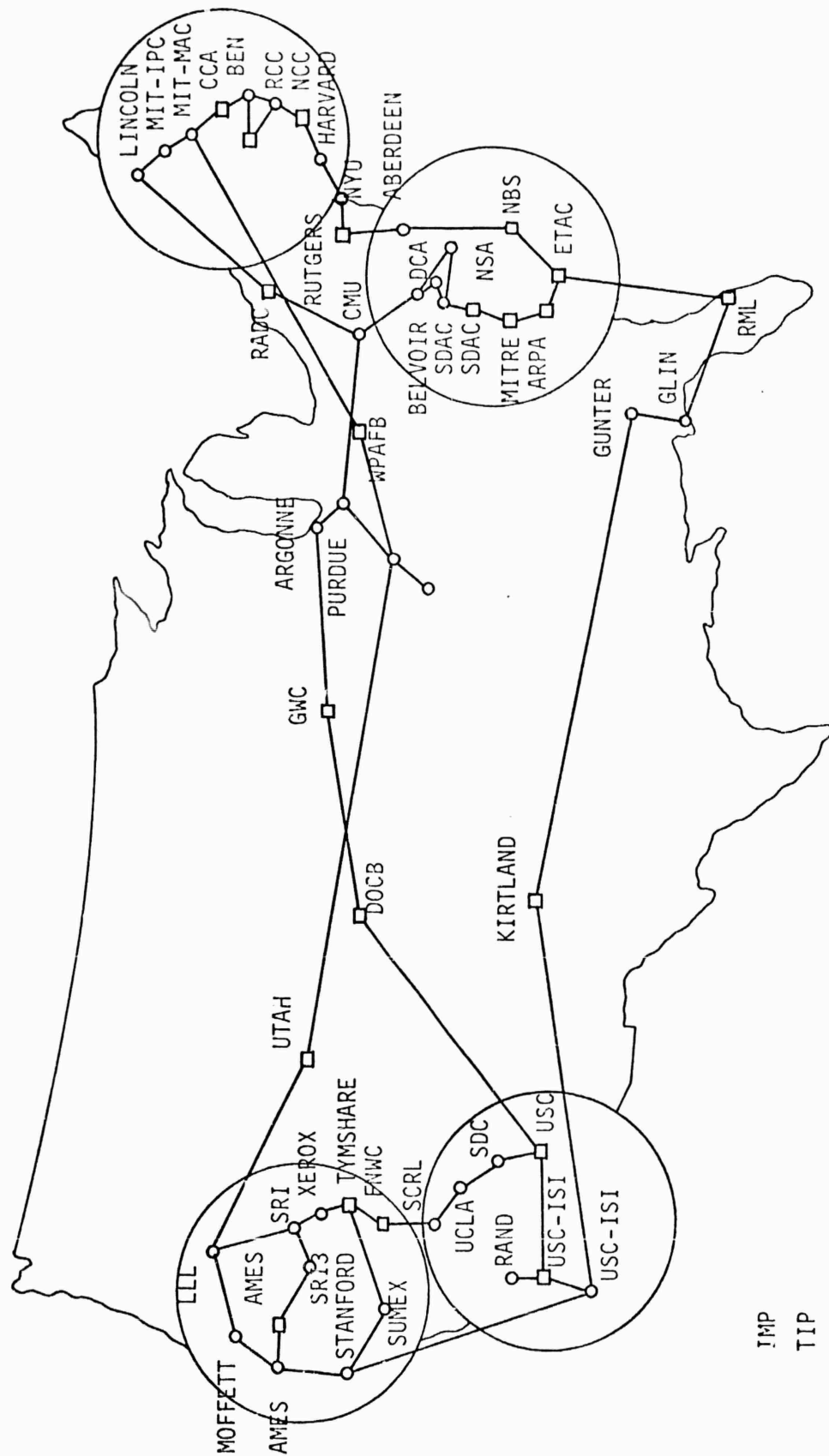


FIGURE 12: ARPANET TOPOLOGY (MAY, 1975)

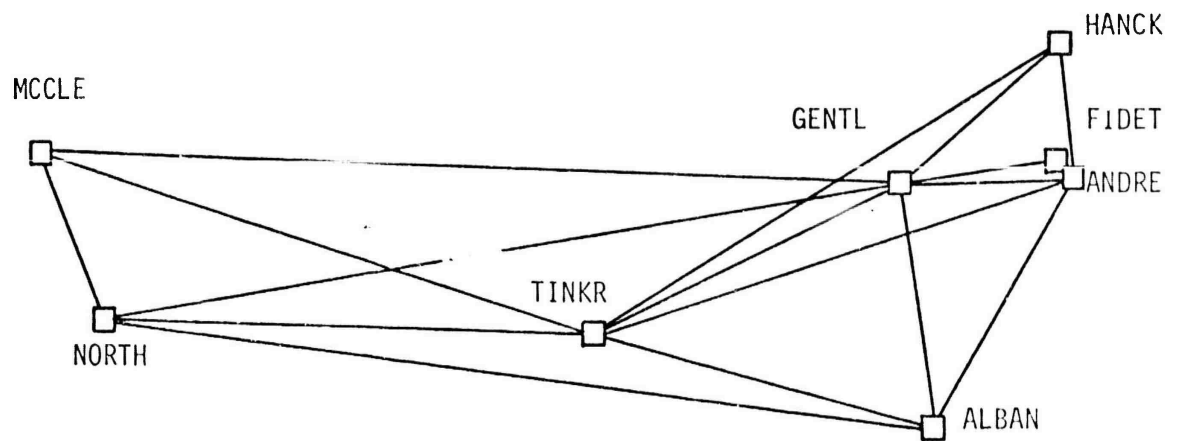


FIGURE 13: AUTODIN II BACKBONE NETWORK TOPOLOGY

Number of switches	=	8
Total data traffic requirement (peak hour)	=	1445 Kbps
Average data packet text portion length	=	1500 bits
Maximum data packet text portion length	=	2000 bits
Packet header size	=	150 bits
RFNM packet size	=	150 bits
Average number of RFNM packets/data packet	=	1
Routing overhead	=	7%

Gateway-Half Virtual Net

For the intergateway links, we assume the following characteristics:

Average data packet text portion length	=	600 bits
Maximum data packet text portion length	=	1000 bits
Packet header size	=	150 bits
RFNM packet size	=	150 bits
Average number of RFNM packets/data packet	=	1
Routing overhead	=	7%

Notice that in the gateway-half virtual net, we assume the flow control is done on a link-by-link basis. Thus, RFNM packets and acknowledgments are required between each two adjacent gateway-halves.

The ARPANET-AUTODIN II data base is significantly different from the model 4-net data base considered in Section 7.6.2. Following are the main differences:

- (a) ARPANET and AUTODIN II each roughly span the entire continental United States. For the 4-net model, each net covers a distinct area of the continental United States.
- (b) ARPANET has a large number of switches, but very low level of traffic. AUTODIN II has very few backbone switches, but the traffic level is high. Hence, the interconnection of these two very dissimilar networks poses an interesting problem. For the 4-net model, each net was comparable in size and traffic magnitude.
- (c) The switch distribution for both ARPANET and AUTODIN II are concentrated on the East coast and the West coast. The switch distribution for the 4-net model is roughly uniform.
- (d) Neither ARPANET nor AUTODIN II were designed optimally for their respective throughput level. Consequently, both have spare capacities for additional traffic. For the model 4-net data base, each net was optimally designed for the local traffic.

Below we evaluate the average packet lengths and the average protocol overheads for the local packets and the internet packet in the local nets and the gateway-half virtual net.

Local ARPANET packets in ARPANET

The local packets refer to the data packets for the original local switch-switch requirements. For this data base we obtained:

$$\left(\begin{array}{c} \text{average protocol} \\ \text{overhead} \end{array} \right) = 50\%$$

$$\left(\begin{array}{c} \text{average packet} \\ \text{length} \end{array} \right) = 450 \text{ bits}$$

Local AUTODIN II packets in AUTODIN II

The local packets refer to the data packets for the original local switch-switch requirements:

$$\left(\begin{array}{c} \text{average protocol} \\ \text{overhead} \end{array} \right) = 20\%$$

$$\left(\begin{array}{c} \text{average packet} \\ \text{length} \end{array} \right) = 900$$

Internet Packets in ARPANET and AUTODIN II

The internet packets refer to the data packets for the original requirements between switches in ARPANET and AUTODIN II. In this case, both local and internet headers are required:

$$\left(\begin{array}{c} \text{average protocol} \\ \text{overhead} \end{array} \right) = 75\%$$

$$\left(\begin{array}{c} \text{average packet} \\ \text{length} \end{array} \right) = 525 \text{ bits}$$

Internet Packets in the Intergateway Links

In this case, the only packet header is the internet packet header:

$$\left(\begin{array}{c} \text{average protocol} \\ \text{overhead} \end{array} \right) = 50\%$$

$$\left(\begin{array}{c} \text{average packet} \\ \text{length} \end{array} \right) = 450 \text{ bits}$$

We make the following assumptions on the traffic distribution:

1. The intranet requirements are fixed, i.e., the total local ARPANET throughput is set at 57 Kbps, while the total AUTODIN II throughput is set at 1445 Kbps. This is done because the ARPANET throughput level is so low, it is not meaningful to distribute the total ARPANET throughput among local and internet requirements. Moreover, to reflect the realistic environment, it is probably not meaningful to scale up the ARPANET traffic level.
2. The internet traffic requirement between ARPANET and AUTODIN II is distributed uniformly among all the switch pairs (i.e., pair of switches a and b, with a in ARPANET and b in AUTODIN II).

The facility costs/capabilities are the same as that for the model 4-net design (see Table 1), except that for ARPANET, regular IMP's are used, with a cost of \$2K/mo., and total throughput of 250 Kbps. The Pluribus IMP's are used as the AUTODIN II switches.

7.6.4. Design Results on ARPANET-AUTODIN II Data Base

Two basic sets of experiments were conducted on the interconnection of ARPANET and AUTODIN II. In the first set, the topologies and link capacities of both the ARPANET and AUTODIN II are assumed fixed. For each selected set of gateway-halves, we find the maximum amount of internet traffic requirement that can be channeled through the gateway-halves before either ARPANET or AUTODIN II become congested. In the second set, we examine the cost differences

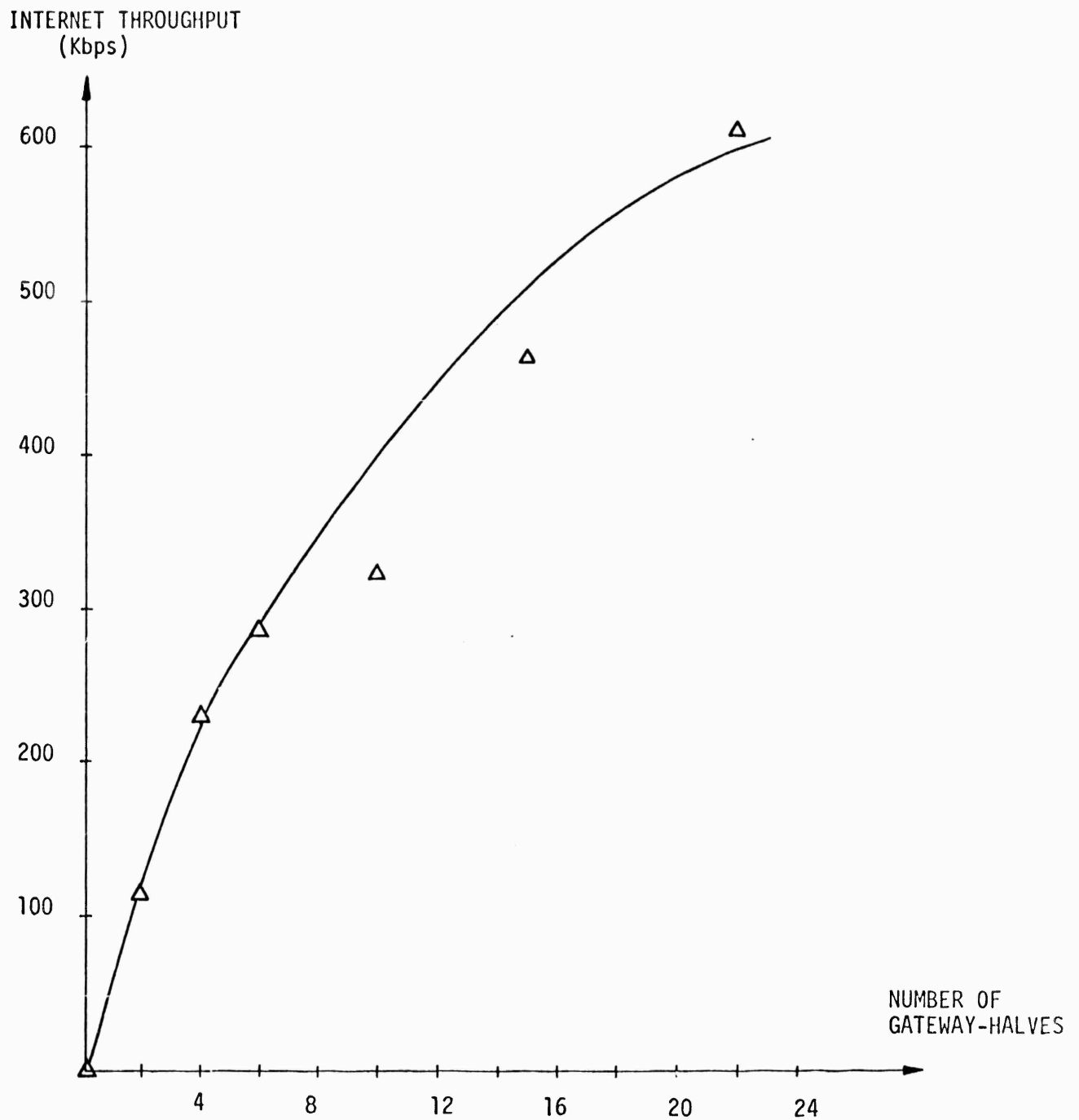
between designs allowing local net modifications and designs not allowing local net modification.

Maximum Internet Throughput vs. Number of Gateway-Halves Used

Suppose that in internet communication, the topologies and link capacities of neither ARPANET nor AUTODIN II are allowed to be modified. This is very likely to be the situation for most internet communication. It is then of interest to find out the maximum amount of internet requirement that can be accommodated for a given set of gateway-halves. We have performed numerous experiments on different sets of gateway-halves in ARPANET and AUTODIN II, and the results are summarized in Figure 14. For convenience, we used the total number of gateway-halves in both nets as the parameter. It was found that for all of the designs considered, ARPANET capacity is always the limiting factor in internet throughput. In Figure 15, we plot the maximum internet throughput versus the number of gateway-halves used in ARPANET. It can be seen from both Figures 14 and 15 that the internet throughput level is slightly concave with respect to the number of gateway-halves used. Moreover, with just a few gateway-halves, an internet throughput level of 100-300 Kbps can be easily achieved.

Total System Cost Comparison Between Allowing Local Net Modification and Not Allowing Local Net Modification

Suppose both ARPANET and AUTODIN II are allowed to be modified. Then intuitively, for the same internet throughput level, the total system cost should be lower than when the local nets are not allowed to be modified. In Figure 16 we plot the total system costs for both cases with the internet throughput level as the parameter. The cost versus throughput curves were also shown for different unit component costs. Examining Figure 16, one can observe that;



F1 JRE 14: INTERNET THROUGHPUT VS. NUMBER OF GATEWAY-HALVES USED IN THE SYSTEM; ARPANET-AUTODIN II DATA BASE; FIXED LOCAL NETS

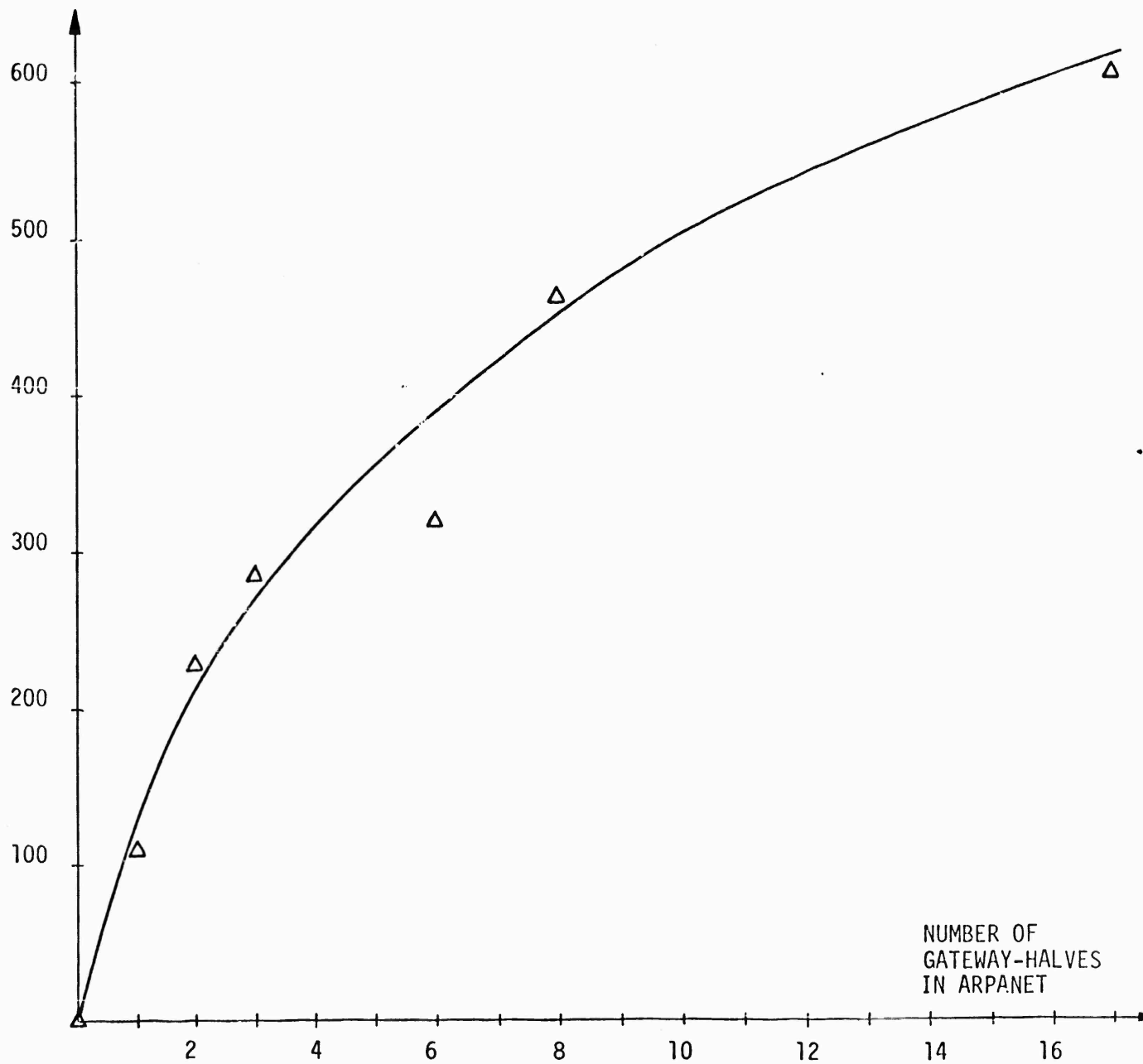
INTERNET THROUGHPUT
(Kbps)

FIGURE 15: INTERNET THROUGHPUT VS. NUMBER OF GATEWAY-HALVES USED IN ARPANET;
ARPANET-AUTODIN II DATA BASE; FIXED LOCAL NETS

TOTAL SYSTEM COST
(K\$/MO.)

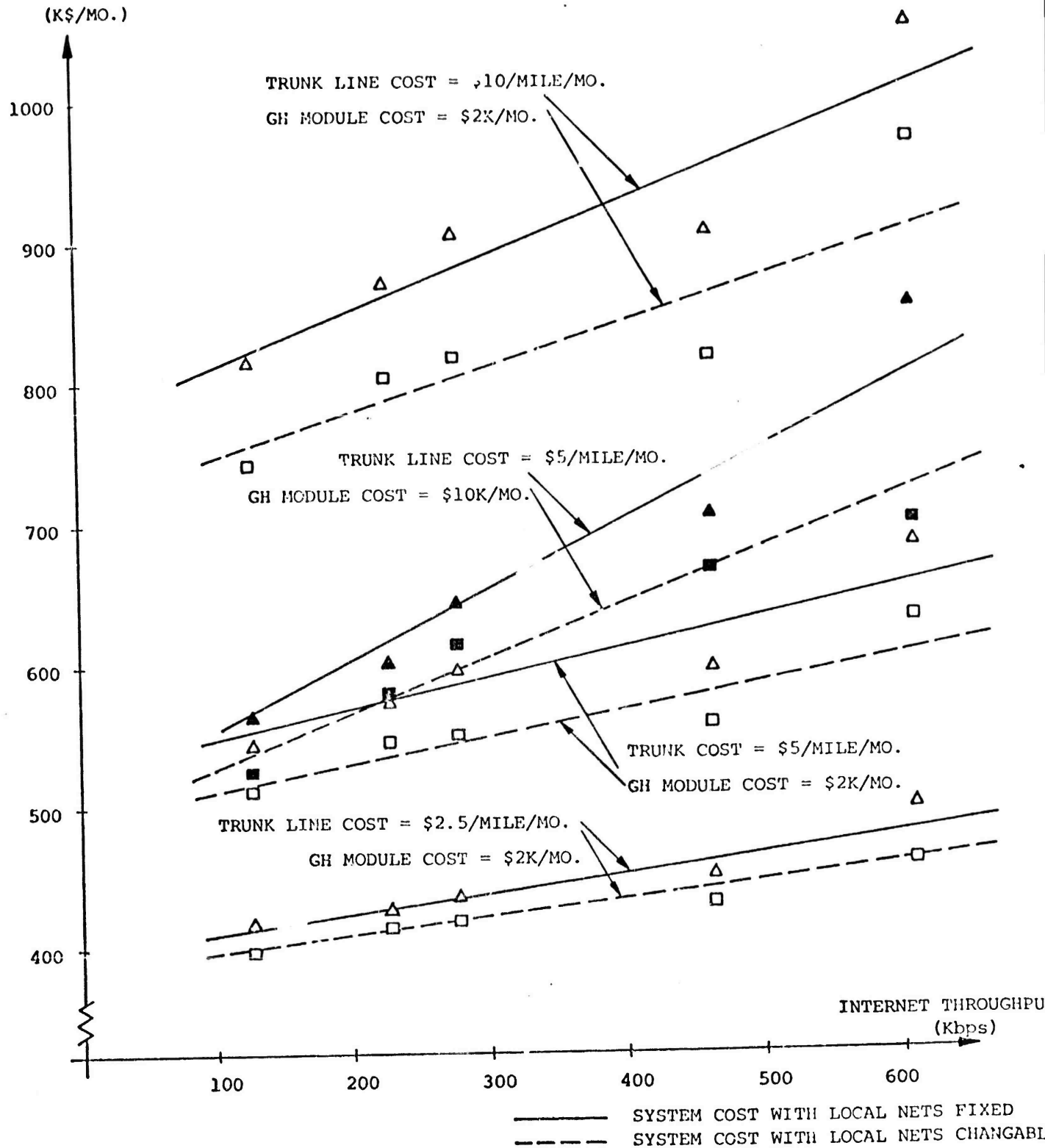


FIGURE 16: TOTAL SYSTEM COST COMPARISON BETWEEN DESIGNS
WITH LOCAL NET FIXED AND DESIGNS WITH LOCAL NETS MODIFIABLE;
ARPANET-AUTODIN II DATA BASE

1. For the same unit communications cost, (i.e., trunk line mileage cost), the difference in total system cost between designs with local nets fixed and designs with local nets changeable is nearly constant regardless of the total internet throughput level.
2. The difference in total system cost between the two types of designs is quite sensitive to changes in unit communications cost, and is less sensitive to changes in unit gateway-half module cost.
3. Suppose the unit gateway-half module cost is expensive (for example, \$10K/mo/module,) as is one of the cases considered in Figure 16. Then the cost differences between designs with local nets fixed and designs with local nets changeable increases as the internet throughput level increases. This can be explained as follows: If the local nets are fixed, then as the internet throughput level increases, more gateway-halves are needed, as is shown in Figures 14 and 15. On the other hand, if the local nets are modifiable, then the same internet throughput level can be achieved with fewer gateway-halves by doing some local net modifications. Consequently, with expensive gateway-half modules, the cost differences between the two types of designs increases with the internet throughput level.

Since one can predict with reasonable confidence that both the unit communications cost and the unit hardware cost will continue to decline, the above observations indicate that the cost penalty paid by requiring local nets fixed in internetworking will become less and less significant. At the base unit cost used in this study - \$5/mile/month for the 50 Kbps trunk lines and \$2K/month for a gateway-half module with 200 Kbps throughput (which are estimates of the current market prices) - the extra cost paid by the fixed local net designs amounts to less than 8% of the total system cost.

7.7 CONCLUSIONS

In this chapter the topological design problem of interconnecting packet switched networks was studied.

The gateway-half model was adopted as the medium of internet connection. Using the gateway-halves as the higher level nodes, a hierarchical internet routing model was developed. A reduced internet topological design problem was then formulated. A solution approach, using extensions of existing techniques, was also presented. The solution procedure was implemented in a PDP-10, and was applied to study the interconnection problem in a multi-network model, and the interconnection of ARPANET and AUTODIN II.

The following observations emerge from the studies of interconnecting 4 equal size networks:

1. The higher the proportion of internet requirement, the higher the total system cost.
2. If neither the local net topology nor link capacities are allowed to change, then gateway-halves are needed at at least half of the switch locations.
3. If only a moderate number of gateway-halves are used, then good internet design can be obtained by allowing modifications on the local link capacities.
4. The cost for an interconnected packet-switched system is of the same order as the cost for an integrated packet-switched system, on the same set of switches.

On the ARPANET-AUTODIN II interconnection study, the assumption was that the local traffic requirements are fixed. Studies were then carried out to determine the maximum internet throughput level for various number of gateway-halves. Parametric studies on the cost comparison between designs with local nets fixed and designs with local nets changeable were also carried out. It was found that at the base unit cost (\$5/mile/mo. for 50Kbps trunk lines and \$2K/mo. for the gateway-half modules), the cost differences amounts to only 5-10% of the total system cost. It was also found out that the cost differences are more sensitive to changes in the unit communications cost, and less sensitive to changes in the unit gateway-half module cost.

Internet topological design is a new area of research (as is the entire area of network interconnection). Hence, there are many issues open for further investigation. We indicate a few of the relevant issues here:

1. General hierarchical routing strategies: The internet model developed in this paper assumes a very special hierarchical structure: Each Host is associated with a unique switch, and each switch is associated with a unique gateway-half in the same network. In a more general context, each Host (switch, respectively) can associate with several switches (gateway-halves, respectively) in the same net. This allows more flexible and reliable host-switch connection and internet connection, and better flow and congestion control. Consequently, hierarchical routing strategies which allow each node to select one of several higher level nodes as its "homing nodes" are desirable.

2. Local net design considerations in the multi-network context: The local net design approach used in this study takes only the local (switch to switch, switch to gateway-half) requirements into account. Thus, the local net design and gateway-half virtual net design are essentially two separate problems. This approach is similar to many of the national telephone systems: Usually a certain number of cross-country channels between international gateways are reserved for international traffic; these channels can be regarded as capacity taken away from the resident national net. However, other local net design strategies with better capacity-sharing scheme for the local-internet traffic may be more desirable from the cost-effectiveness viewpoint.
3. General multi-network interconnection and integration: The problem addressed in this paper concerns only the interconnection of packet-switched networks. However, generally, the packet-switched networks serve as the backbones for large distributed networks in a multi-level architecture. Consequently, the interconnection and/or integration problem should be most appropriately addressed in the total system context.

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10. AVAILABILITY/LIMITATION NOTICES This document has been approved for public release and sale; its distribution is unlimited.			
11. SUPPLEMENTARY NOTES None		12. SPONSORING MILITARY ACTIVITY Advanced Research Projects Agency, Department of Defense	
13. ABSTRACT New research results on the following major questions are reported: Results on integrated DOD Voice and Data Networks include: analytical models for determining blocking and delay on an integrated link and numerical investigation as a function of traffic and design variables; algorithms for integrated network design were developed and programmed. The program is capable of designing networks for voice traffic, signaling and data traffic. A circuit switch model for determining switch and network transit delays for circuit connection set-up was developed. A methodology for classification of telecommunications routing algorithms was developed. Results on topological gateway placement include an algorithm and program for interconnecting packet switched networks, studies of cost/performance tradeoffs, and an application to interconnect the ARPANET and AUTODIN II. In the packet radio area models were developed to estimate network initialization as a function of number of repeaters, transmission rates of repeaters and station, and operation disciplines. Finally, cost trends for large volume packet switched data networks are derived which incorporate switching and transmission costs, satellite and terrestrial channels and local distribution.			
14. KEYWORDS - Computer networks, communication networks, terrestrial and satellite networks, packet radio networks, throughput, cost, delay, blocking, ARPA Computer Network, store-and-forward, packet switching, circuit switching, integrated switching, gateways.			